Vol. XXII No. 1 March, 1977

The SPEX Speaker

INDUSTRIES, INC. · 3880 PARK AVENUE · METUCHEN, N.J.,08840 · ☎ (201)-549-7144

MEASURING THE LIGHT INFINITESMAL

Stephen Arnold
New York University, Radiation and Solid State Lab., Washington Square, New York, N.Y. 10003

In this world of digital displays, almost all transducers generate analog signals. Whatever the device, whether it is making electrical, magnetic, mechanical, or optical measurements, its output signal is likely to be analog rather than digital. One of the few exceptions is the photomultiplier tube (PMT). Its digital nature stems from the 1905 discovery by Einstein that the ejection of electrons from illuminated surfaces may be explained if light is considered to comprise individual particles or photons. The rain of photons on the cathode of a PMT produces characteristic charge pulses at the anode, the "shot effect" (Fig 1). Although the shot effect entails nothing but burdensome noise in ordinary dc measurements, it is the basis of a technique, called photon counting (PC). Discrete pulses from the PMT are first sent to amplifying circuitry which discriminates between electrons that originate at the cathode of the PMT and those generated elsewhere down the dynode string. The amplified pulses can then be converted to a count-rate in analog form or, alternatively, can be fed directly to digital computational instrumentation for processing and storage.

The ability of the PC method to detect very low levels is continually opening new frontiers. Although PC was first proposed for astronomy (1), its principal applications today are terrestrial. The technique has improved the S/N in Raman spectroscopy (2), and many applications have been made in fluorometry. A good example of the importance of PC in molecular fluorescence is the detection of SO_2 in air at the parts per billion level. (3) Communications research has also been aided by PC. Laybourn and others (4) have constructed a system for measuring light-scattering losses in glass at levels down to 0.2 dB/km. By counting photons sequentially in two scalers, information may be acquired about the influence of a periodically changing variable. In this way energy-transfer mechanisms in crystals are probed by tracking the small changes in the fluorescence of the crystals under periodically changing electric and magnetic fields (5,6). Other low-light-level measurements benefiting from PC are in astronomy, phosphorescence, thermoluminescence, chemiluminescence, Rayleigh scattering, Mie scattering, and Brillouin scattering.

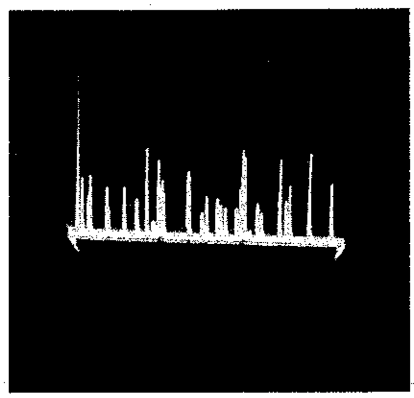


Fig 1 Current spikes from photons striking the photosensitive surface of a PMT and subsequent amplification by the PMT itself. These pulses, varying widely in amplitude and random with time, are treated as unwanted "shot noise" in older methods of light measurement. As the "shot effect" they constitute the sensing parameter for photon counting.

Even at higher light levels, PC, by virtue of its improved precision, allows measurements of small differences not easily achieved by analog sensing. Examples abound in absorption spectrometry, polarimetry, and optical rotary dispersion where minute differences in large signals are significant.

From an instrumental viewpoint eliminating analog-to-digital converters is often sufficient reason for switching to PC. But other salient advantages accrue:

- improvement of signal-to-noise ratio (S/N) resulting in lowering the threshold of detectable light and improving the ability to measure small differences in large signals.
- reduced effect of voltage changes on the PMT output.
- much higher efficiency in smoothing noise through digital integration permitting longer integration times than can be realized by other means.

To emphasize and understand the intricacies and advantages of PC it would be well to review older methods of data processing for light-measuring techniques. Oldest and simplest is DC where the anode current of the PMT is measured directly with a picoammeter; usually a separate unit supplies the negative high voltage. Compared to newer techniques, noise associated with DC amplification is several times higher. Adding a resistor/capacitor (RC) low-frequency bandpass filter is the most common means of reducing inherent noise. In essence this serves as an averaging device, smoothing out fast transients. But the RC filter is also the least efficient means of improving S/N. For example, if a filtering time constant of 1 sec is selected, it will take 5 time constants or 5 sec before an uncharged capacitor reaches 99.7% of the final value. An error of even 0.3% can be significant in many photometric applications. The slow response of the RC filter requires very slow scanning speeds in spectrophotometry or long waits by the analyst to obtain a final measurement in a static system.

To improve S/N and reduce the amount of measurement time associated with RC smoothing, modulating techniques and tuned amplifiers have been employed. By modulating or chopping the signal, as is frequently done with infrared detectors and in double-beam photometry, the amplifier can be tuned to the modulating frequency. Noise in the signal outside the amplifer bandpass is rejected. This method does not eliminate or reduce noise within the amplifier bandpass, and it is usually necessary to add an RC network after the tuned amplifier.

But, like trading in the horse for the automobile, modulating the signal did not prove wholly satisfactory. Any instabilities in the chopping frequency resulted in an increased bandpass and an aggravation of the noise. To overcome this, lock-in (synchronous) amplifiers were devised. The frequency response of such amplifiers is locked to the chopper frequency; any drift is tracked by the amplifier, permitting a very narrow bandpass for the amplifier.

Despite these advances, all three techniques share several troublesome characteristics. The first relates not to the means of measurements but to fluctuations in the high voltage on the PMT. Changes in the PMT high voltage cause the gain, and hence output current, to vary by ten times as much. Since the instability of most commercial high-voltage supplies is in the order of 0.01%, fluctuations of 0.1% in the output current—modulated or DC—can be expected. This imposes a limitation not only on precision and responsivity but also on the ability of the amplifier to distinguish between two signals of nearly equal magnitude. In absorption spectrophotometry this sets the minimum detection limit. That is, the concentration must be sufficient to result in a change in transmitted light of at least 0.1% before the concentration can be detected. In DC and modulated filtering, noise generated by the electronic components is introduced into the actual signal. This l/f noise can never be eliminated, even with lock-in amplification, since noise of all frequencies within the amplifier bandpass is amplified along with the signal.

Counting individual photons makes possible a digital integration technique promoting further improvement in S/N over lock-in amplification. By fast switching of a gate, pulses are counted and stored for any amount of integration time. With this form of digital integration, l/f noise is eliminated, and very long integration times are possible. The integration time can be adjusted for any desired S/N.

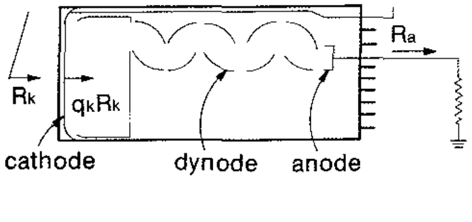


Fig 2 Within the photomultiplier photons are first converted to electrons which then cascade down the dynode chain in increasing numbers due to secondary emission occurring at each surface. R_a/R_k, the rate of pulses collected at the anode divided by the rate of photons striking the cathode, is a measure of the efficiency of the PMT.

A number of experimenters have made careful comparisons between PC and lock-in amplification. Alfano and Ockman (7) have shown that S/N for detection of the 992 cm^{-1} Raman band of benzene is improved by a factor of 4 through PC. Murphy and others (8) have compared PC and lock-in detection in atomic-fluorescence spectrometry and shown that the PC detection limit for zinc is better by a factor of 35.

Theory of Photon Counting

Photons striking the cathode of a photomultiplier (Fig 2) at a rate R_k generate photoelectrons with a cathode quantum efficiency q_k, so the rate of photoelectrons leaving the cathode is q_kR_k. Only a fraction, f, of these photoelectrons is collected by the first dynode of the PMT; thus the number of electron pulses per sec amplified by the dynode structure is fq_kR_k. In the dynode chain each of these pulses is amplified so that it generates between 10^5 and 10^7 electrons at the anode. This amplification is known as the charge gain, G, of the photomultiplier. With no pulse loses in the dynode structure, the usual case, the rate of anode pulses R_a is

$$R_a = fq_kR_k. \quad (1)$$

The ratio of the anode pulse rate R_a to the photon rate R_k is fq_k. This throughput efficiency, or overall quantum efficiency, is wavelength dependent but typically does not exceed 30%. Put another way, for every ten photons impinging on the photocathode as many as three charge pulses appear at the anode.

The omission of G in (1) points up the stability advantage of PC. Unlike the situation in DC amplification, the anode voltage on a PMT can vary by as much as 50V without disturbing the PC output. This idealized picture of gain variations, however, is far from complete. Although G is taken to be a constant for current measurements, the value of G is really statistical average, $\bar{G}$, because gain at a given voltage varies from one anode pulse to the next. In addition, some charge pulses at the anode are nonphotonic. Thus, even in the dark, thermionic emission releases electrons at the cathode as well as at the dynodes. The key to optimum PC is to distinguish between photonic and nonphotonic anode pulses so that relatively few nonphotonic ones contribute to the final count.

In photon counting a pulse-height discriminator separates photonic from nonphotonic anode pulses. To understand how this device operates it is first necessary to become familiar with the pulse-height distribution of a typical PMT. Pulse heights are measured by

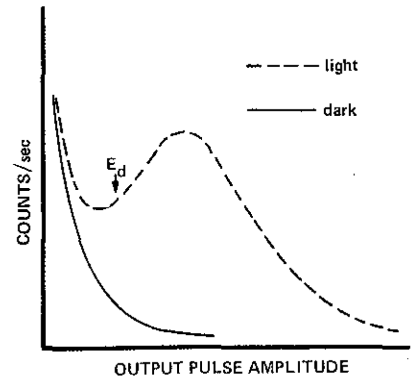


Fig 3 A graph of the PMT output as count rate vs amplitude of the pulses illustrates the difference in distribution of pulse heights between a PMT totally in the dark and illuminated. By setting a threshold voltage (discriminator level) of E_d and rejecting all pulses less than that amplitude, much of the "dark" noise can be ignored, and the light-to-dark-count is optimized.

converting the anode charge pulses to corresponding voltage pulses. Since PMT pulse widths are relatively constant, the peak current, and therefore the peak voltage, will be proportional to the charge in each pulse. Fig 3 shows the distribution of voltage heights from a typical PMT. With no light incident on the photocathode most pulses are relatively low. This is due to the fact that most thermionic electrons originate from the dynodes. Since the charge gain of the first dynode is considerably greater than one for an electron emitted from the cathode, the gain for thermionic electrons originating at the dynodes is lower than that for photoelectrons and, therefore, the pulse-height distribution in the dark falls off toward higher pulses. In the presence of light a pronounced increase in higher pulses occurs, as shown in Fig 3. By introducing a circuit which allows only pulses above a specified voltage to be counted a large proportion of the dark count is thus rejected. This relative pulse-height discrimination is one way in which PC improves S/N.

A typical circuit for PC is diagrammed in Fig 4. The first component following the PMT anode is an amplifier to boost the output pulses to an acceptable level for the discriminator. This amplifier can be either charge-sensitive or voltage-sensitive as will be explained later. The discriminator level following the amplifier is adjustable. If we suppose for a moment that the pulse-height distribution in Fig 3 was taken from the input to the discriminator, then the arrow in this figure represents the approximate location E_d at which the discriminator level should be set to maximize the light-count to dark-count ratio. In early applications of PC an upper-level and lower-level discriminator—a pulse-height

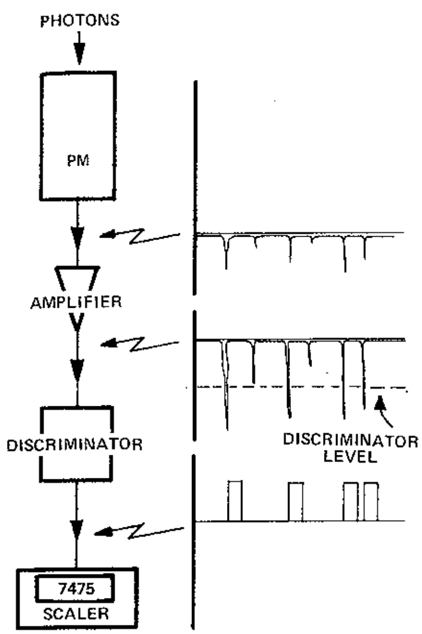


Fig 4 This simplified block diagram of a photon counter depicts the fundamental principle of the DPC-2 PC measurement.

window—was advised. The three sources of noise which created a need for the upper-level discriminator were cosmic ray muons, after pulsing, and radioactive contamination of tube materials. In modern PMTs the latter two noise sources have been minimized through careful dynode design and the selection of materials with low radioactivity. Of course, the muon problem cannot easily be eliminated, but since this noise source adds less than one count per sec, an upper-level discriminator is no longer warranted.

A simple method for maximizing the light-count to dark-count ratio, while simultaneously recording as many light counts as possible, is to observe the count rate vs. PMT voltage. For a fixed discriminator level, as the PMT voltage is increased the charge per pulse will continuously rise until nearly all of the photonic pulses exceed the discriminator level. At this point the count rate will reach a plateau as shown in Fig 5. The dark count does not usually exhibit such a plateau but continues to increase as shown. The optimum voltage for the PMT is just above the knee of the count rate vs. voltage curve as indicated by the arrow in Fig 5. Note that at this point the count rate is virtually independent of high-voltage fluctuations.

Another important advantage of PC is enhancement of S/N with counting time due to the well defined statistics by which the method operates. For a broadband thermal light source (and to a good approximation for other light sources) the rate of arrival of photons is random. This random process may be described by a Poisson distribution (9) according to which the probability P of q photons arriving within an interval of time t is

$$P = \frac{(R_k t)^q \, e^{-R_k t}}{q!} \qquad (2)$$

where R_k is the average photon rate. Since the photoelectrons are emitted by the incident photons they follow the same statistics. The most important consequence of the probability distribution in (2) is that the standard deviation σ of the number of photonic pulses counted per interval is equal to the square root of that number. If 100 photonic pulses are counted in a given time, then in the next interval of time the odds favor a fluctuation of no more than ten counts. Defining one standard deviation as noise, the S/N ratio in this experiment is 10:1. If the time interval is extended so the average number of counts is 10^6, then the one standard deviation noise is 10^3 and S/N is improved to 1000:1. The actual rate of pulses R_a' counted, however, will contain a rate of signal (photonic) pulses R_p plus a rate of dark pulses R_d. In general then

$$R_a' = R_p + R_d. \qquad (3)$$

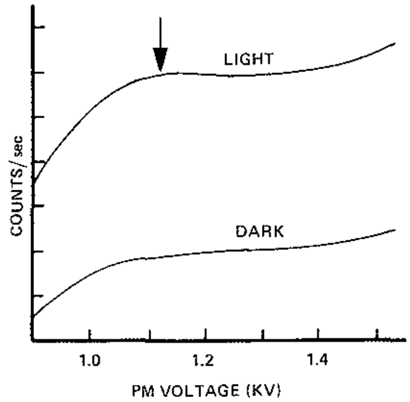


Fig 5 Optimum voltage applied to a PMT in the pulse count mode is determined by a count rate vs voltage plot, with the best voltage, shown by the arrow, toward the center of the plateau where a voltage change has the least effect on the count rate.

Assuming the anode pulses are measured over a fixed time t and the dark pulses are measured over the exact same time, the difference in these two counts will be $R_p t$, and S/N in this difference will be given by (10)

$$\frac{S}{N} = \frac{R_p \sqrt{t}}{\sqrt{R_p + 2R_d}} \qquad (4)$$

We see therefore that S/N increases as the square root of the measurement time.

PC is not without its limitations. One of these is the restriction in maximum acceptable light level. From the moment a discriminator begins to produce an output pulse, any other pulse arriving within the dead time t_D will be curtly ignored. Clearly, if the average rate of anode pulses R_a is comparable to pulse-pair resolution, the output of the discriminator R_o will be considerably less than R_a. Fortunately, this situation can be analyzed because of the random nature of photon statistics. For a measurement time t the total number of discriminator output pulses is $R_o t$. Each of these pulses provides a dead time t_D so the total time during which the system will not accept further pulses is $R_o t t_D$. Therefore, this dead time is a fraction $R_o t_D$ of the total time and the fraction of time in which the system is "alive" is $(1 - R_o t_D)$. This is the proportion of incoming pulses appearing at the output of the discriminator. Mathematically,

$$R_o/R_a = 1 - R_o t_D. \qquad (5)$$

Therefore, to achieve a better than 95% accuracy in counting requires a $t_D < 0.05/R_o$. With an output count rate of 10^6 pulses per sec t_D must be less than 50 nsec. Fig 6 shows a plot of R_o/R_a vs R_o for a system with a dead time of 40 nsec, the maximum dead time specified for the Spex DPC-2 preamplifier/discriminator. In general the system dead time is a function of the amplifier discriminator characteristics as well as the pulse width of the PMT. For this reason the parameter which is usually given to characterize the amplifier-discriminator is the pulse-pair resolution which corresponds to the dead time for an infinitesimal PMT pulse width.

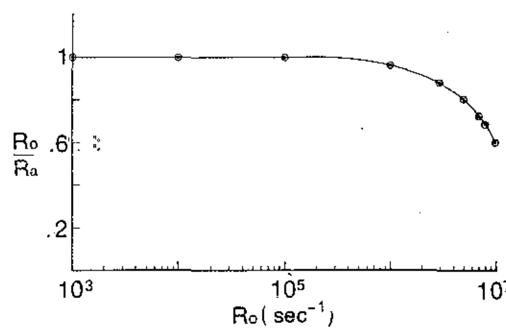


Fig 6 The efficiency of an amplifier-discriminator R_o/R_a vs the output count rate R_o as given by (5) for a system dead time of 40 nsec. Even at a count rate of 10^6/sec the accuracy of such a system is 95%. This performance is typical of that which may be obtained with the DPC-2 and a moderately fast PMT.

The Spex Single Photon Amplifier Discriminator (SPAD)

Discrete photon amplifier-discriminators can be classified into one of two design categories: voltage sensitive and charge sensitive. In a voltage-sensitive amplifier a current pulse from the PMT is converted to a voltage pulse by means of a resistor and then amplified with a typical gain of one hundred. The maximum amplitude of the pulse is proportional to the maximum current of the anode pulse. By contrast, charge-sensitive amplifiers take advantage of the ability of a capacitor to integrate charge. By placing a capacitor C in the feedback circuit of an inverting amplifier, such as the one in Fig 7, the output voltage of the amplifier is proportional to the total charge contained within the pulse.

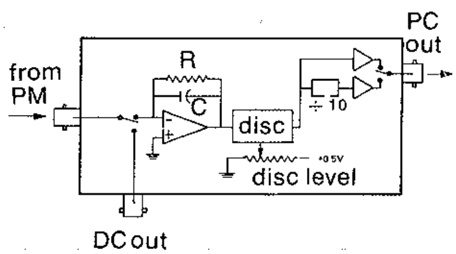


Fig 7 Sensing the charge on capacitor C, the preamplifier/discriminator (SPAD) of the DPC-2 departs from the usual method of voltage-sensitive preamps. The initial amplification state, charge sensitive as opposed to voltage sensitive, strongly rejects background such as RF noise.

The charge-sensitive amplifier is preferable because it is less sensitive to capacitively coupled noise sources. Its high-frequency gain is the ratio of the coupling capacitance to the feedback capacitance, and this ratio is normally less than one tenth. By contrast, the maximum high-frequency gain of the voltage-sensitive circuit is virtually independent of the coupling capacitance and approximately equal to the normal voltage gain (~100). Even without double-shielded cable at the amplifier input and elaborate RF shielding of the PMT, the Spex charge-coupled single photon amplifier/discriminator (SPAD) all but eliminates noise pick-up so common with older preamps.

The responsivity to direct-coupled current sources such as PMTs may be characterized in terms of the gain r. To a good approximation

$$r = \frac{1}{C}\left\{\frac{RC}{\Delta t}\left[1 - e^{-\Delta t/RC}\right]\right\} \quad (6)$$

where Δt is the pulse width of the charge pulse, and R and C are the feedback resistance and capacitance in Fig. 7. Fig 8 is a plot of the gain vs pulse width for the Spex SPAD. The amplifier gain saturates as the pulse narrows. A pulse 1 nsec wide results in a gain of 6.7×10^{11} V/C. For a typical PMT pulse width of 10 nsec, as indicated by the arrow in Fig 8, r is 5.3×10^{11} V/C. The falloff in r with increasing pulse width desensitizes the charge-sensitive amplifier to direct-coupled charge pulses of long duration.

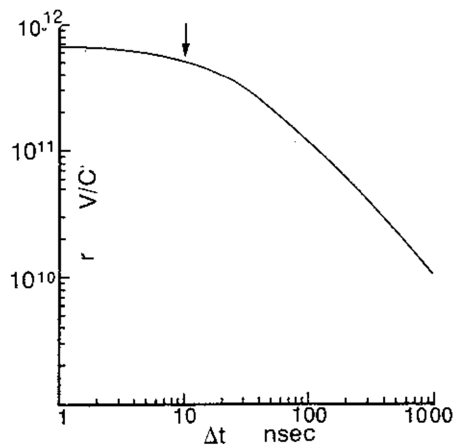


Fig 8 As the input pulse width increases, the gain of the SPAD decreases as shown. Directly coupled noise pulses of moderate to long duration are blocked by the amplifier, providing additional noise rejection. The arrow in this figure shows the gain for a typical photomultiplier with a pulse width of 10 nsec.

The amplifier in the SPAD is followed by a discriminator (Fig 7) with a threshold adjustable from 15 mV to 500 mV. The minimum charge which can produce an output from the discriminator—the charge-discrimination threshold, q_m—is the minimum discriminator voltage level divided by the gain of the input amplifier, so q_m=0.015 V ÷ 5.3×10^{11} V/C=2.8×10^{-14}C. This sets a lower limit on the PMT charge gain G_m to which the SPAD can respond. G_m is equal to q_m/e where e is the charge of an electron. For the SPAD, G_m is therefore 1.8×10^{5}.

The output pulse rate from the discriminator may be counted directly or, to increase dynamic range, divided by ten. Switching in the ÷ circuit allows the Spex DPC-2 photometers to count up to 1.25×10^{6} counts/sec with only a 5% loss. Each output is buffered by a line driver delivering TTL levels capable of providing at least 2 V into a 50Ω load. A summary of the characteristics of the SPAD is given in Table 1.

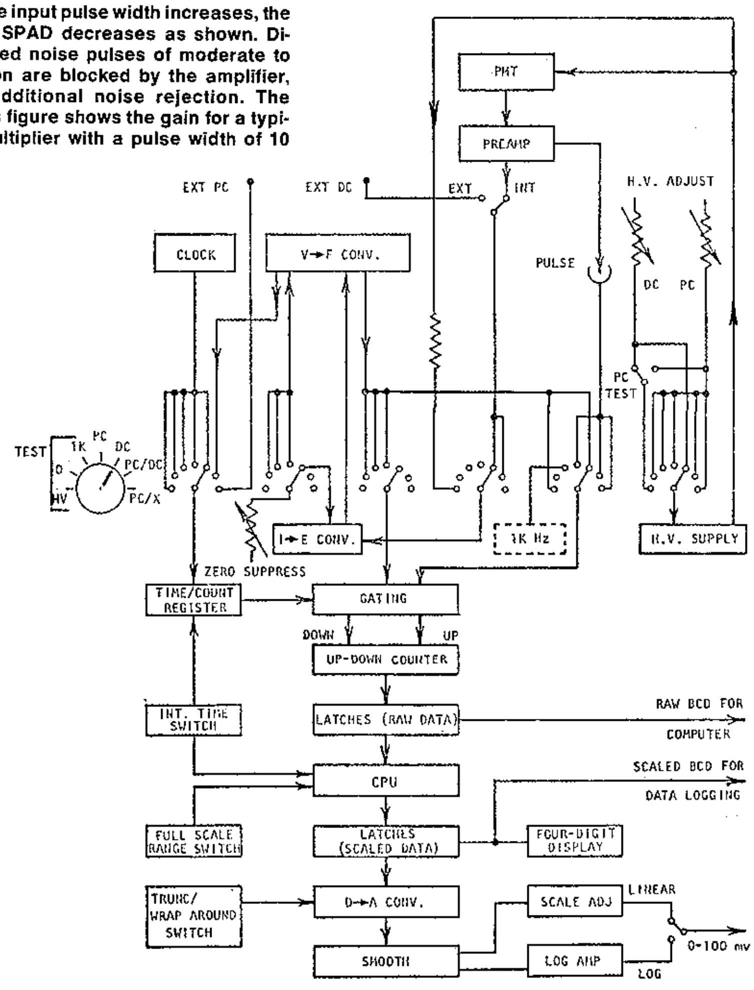


Fig 9 The many functions of the DPC-2 are achieved as shown in this block diagram. Data processing is carried out by a microprocessor unit labeled CPU.

Table 1
SPEX SINGLE PHOTON AMPLIFIER DISCRIMINATOR (SPAD)

Amplifier	
Rise Time	4 nsec
Gain	5.3×10^{11} V/C
Discriminator	
Threshold Voltage	15 to 500 mV
Discrimination Threshold	
Minimum Charge	2.8×10^{-14}C
Gain of Photomultiplier	
Minimum Charge	1.8×10^{5}
Pulse-Pair Resolution	<40 nsec
Output Amplitude (50Ω)	2.5±0.5 V
(100Ω)	3.0±0.5 V
Prescaler	
Division Factor	10
Maximum Input Frequency	100 MHz
General	
Input Power, 50Ω load (max)	+5V, 150 mA
(max)	−5V, 20 mA

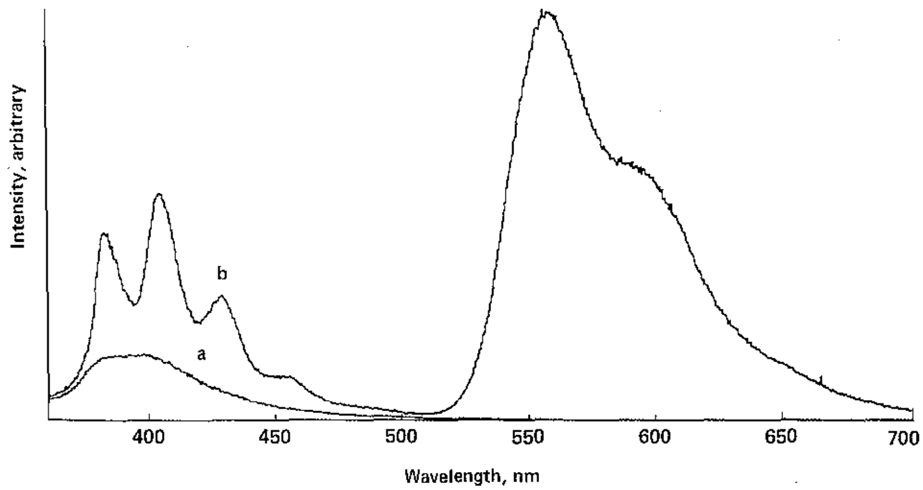


Fig 10 Digital integration of a spectrum by the Spex FLUOROLOG which incorporates the DPC-2. (a) benzene blank; (b) 1 part per 10^6 each, anthracene and rubrene in benzene. Integral of rubrene spectrum (530 to 630 nm) = 3 830 000. Integral of anthracene spectrum (370 to 470 nm) = total integral - integral of benzene = 936 000.

Digital Photometer, Spex DPC-2

The Spex SPAD converts PMT signal pulses to well defined, shaped, discriminated pulses for further signal processing. A digital signal processor and internal high-voltage supply combined with the SPAD form the Spex DPC-2. An analog amplifier for DC mode operation of the PMT as well as a computer interface are also included. Fig 9 is a block diagram of the DPC-2 and following is a discussion of its important features.

1. **High Precision in all Ranges**

Where the signal amplitude is gain-dependent, the stability of all amplification stages in signal processing controls the measurement precision. This consideration becomes critical in applications such as absorption spectroscopy, Raman spectroscopy and fluorescence, where two nearly equal signals must be divided or subtracted. The long-term drift of only 0.01% for the DPC-2 in pulse-count mode, coupled with digital integration, permits differences in signal levels as small as 100 ppm to be measured.

2. **Digital Data Processing for both PC and DC**

Signals are processed by digital circuitry in both PC and DC modes by a central process unit (CPU). At high signal levels, where DC measurements are required, PMT current is converted to a digital signal within the DPC-2 by a voltage-to-frequency circuit, thus allowing further signal processing by the same digital methods as in the PC mode, with all of the advantages retained. Switching from PC to DC does not change the output format of the DPC-2.

3. **A Wide Selection of Digital Integration Times**

Available in the DPC-2 are integration times up to 500 sec to enhance extremely low or noisy signals. From the shortest integration time, 0.1 sec, to the longest, precision of the system is retained, and the true integration time is known. Long integration times can also be of value in measuring the area under a curve produced by a spectral band. Setting the integration time longer than that required to scan the curve causes the signal accumulated to be proportional to the area under the curve. Fig 10 illustrates this feature as applied to fluorescence spectroscopy (11).

The primary advantage of digital integration—saving measurement time—has already been discussed. Its one disadvantage—steplike appearance of the spectrum—can be readily overcome in the DPC-2 with its RC network (Fig 11).

4. **A Built-In PMT High-Voltage Supply with Automatic Changeover between PC and DC**

Optimum voltages applied to the PMT are substantially different for PC and DC. Two preset voltages, automatically selected by switching between PC and DC, make available the extraordinarily broad dynamic range (over nine decades) of the DPC-2 for continuous readout from PC to DC. Either voltage can be displayed on the 4-digit meter for precise voltage determinations. Up to 2000 V are available from the supply, well above the plateau of most modern PMTs.

5. **A Four-Decade Digital Data Display with Nine-Decade Internal Accuracy**

Data entering the DPC-2 in either PC or DC form are initially stored in a counter with nine-digit resolution. After processing the data are displayed on a four-digit panel meter. Meanwhile, the internal calculator-processor of the DPC-2 retains the nine-digit precision. By incorporating a means of displaying and outputting the least significant digits of any given measurement, the DPC-2 is capable of registering a difference in two signals of only one part in 10^9.

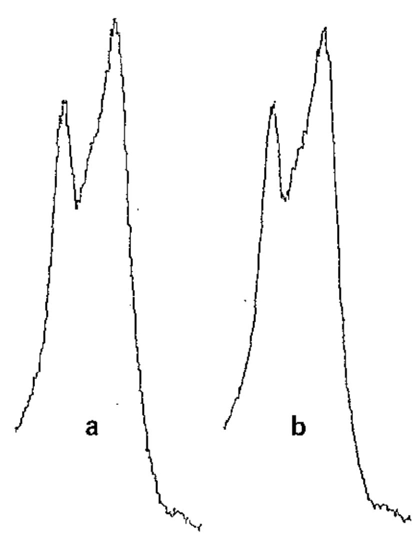


Fig 11 Digitally integrated spectrum (a) exhibits a typical staircase pattern which has been cosmetically smoothed (b) through the variable RC network of the Spex DPC-2. Although not obvious here, RC smoothing can result in some loss of information.

6. **Linear and Logarithmic Analog Outputs**

An analog (DC) output from the DPC-2 allows data to be recorded by a conventional X-Y or Y-T recorder. The analog output can be selected for either of two ranging characteristics, *Truncate* or *Wrap-Around*. Furthermore, the digital display can be "over-ranged" by one decade, while still retaining the most significant digit. With the DPC-2 in the Truncate mode, the analog output will stop at full scale thus keeping the recorder motor from squeaking in protest.

A digital panel display of 1.000 corresponds to a 100 mV analog output for a full scale recorder deflection. In the Wrap-Around mode, when the display exceeds 1.000, it causes the recorder to return to a value equivalent to the last three panel digits. For example, a display of 1.526 produces a single wrap-around of the recorder, with a recorder deflection of 52.6% full scale. A display of 2.526 results in two wrap-arounds by the recorder to again a 52.6% full scale deflection. Up to eight wrap-arounds (8.999 digital meter value) are possible without the need of a range change. The result of a wrap-around is shown in Fig 12. This feature permits measurements of signal differences as small as a few parts per trillion on a conventional recorder.

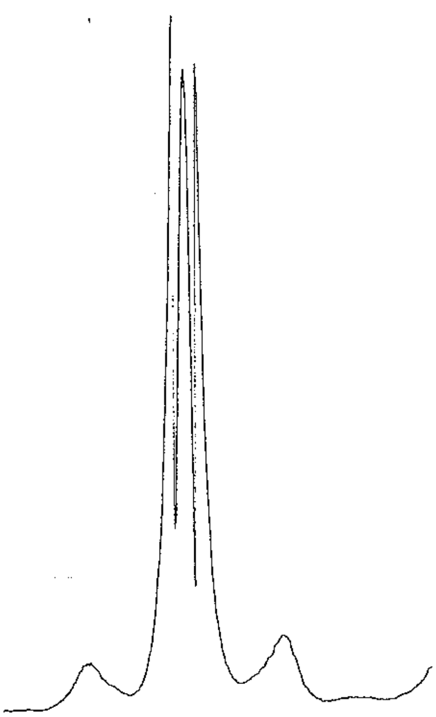


Fig 12 Spectral information from peaks that exceed the full scale recorder range is retained in the wrap-around mode of recording, where the most significant digit of the data register is ignored.

A converter between the CPU and digital panel display can output the $\log_{10}$ of the data to the recorder. The recorder output signal of 0-100mV (full scale) then corresponds to two decades of data. In addition to compressing larger signals and expanding weaker signals, the log feature makes possible recording in absorbance units ($A=\log_{10}I_0/I$) from the ratio modes of PC/DC or PC/X, where X is a TTL pulse input, as discussed in 8. and 9. below.

7. **A Wide-Range Zero-Offset**

Because so many photometric measurements involve a small signal superimposed on a high background, a large zero offset is provided in the DPC-2. In the PC mode backgrounds up to 50000 counts/sec can suppressed; in DC, up to 50 μA.

8. **Division of PC by an External DC Signal (PC/DC)**

Corrections are frequently necessary to compensate for signal variations such as those from unstable sources or those that vary with wavelength. By referencing the signal of interest to a signal derived from the source through double-beam optics, full compensation results in the DPC-2 PC/DC mode, where PC is the photon count rate of the detector, and DC a reference signal. This mode of operation is essential for corrected excitation measurements in fluorometry (11).

Another example of compensation is illustrated by Fig 13. A weak Raman signal from tetrahydrofuran is swamped by noise from laser intensity changes. Monitoring the laser output with a second detector and introducing this signal into the DPC-2 as DC, a PC/DC output eliminates the effects of source fluctuation and provides an excellent Raman spectra unobtainable in the normal (PC) mode.

9. **Division of PC by an External Pulse Count (PC/X)**

Large and slow changes in source intensity, such as encountered in absorption spectrometry when scanning over a wide region, introduce problems in maintaining a relatively constant S/N. Longer integration times are necessary at low light levels than at higher levels.

The PC/X function provides a means of integrating the PC signal for variable or programmed times. The integration time is determined by a selected number of pulses accumulated in the X channel from an external pulse source. By programming the X pulse rate or inputting pulses from a reference detector, and selecting the appropriate X range, constant S/N is achieved.

10. **Digital Data Output and Control Lines Computer Compatible**

The DPC-2 is computer-ready for additional data processing and automation. In TTL, BCD format data from both PC and DC modes can be transferred directly from the data storage register prior to entering the CPU of the photometer to a terminal on the back of the instrument. Control lines and internal clock information are also provided for two-way communication between the DPC-2 and a computer or peripherals. Not only are the raw data available but data that have been scaled or corrected can be fed into other digital equipment. When this is done all nine digits are retained to optimize precision. Included at the output connector are lines for *inhibit count, count gate,* and *data ready* information. Specifications for the DPC-2 are given in Table 2.

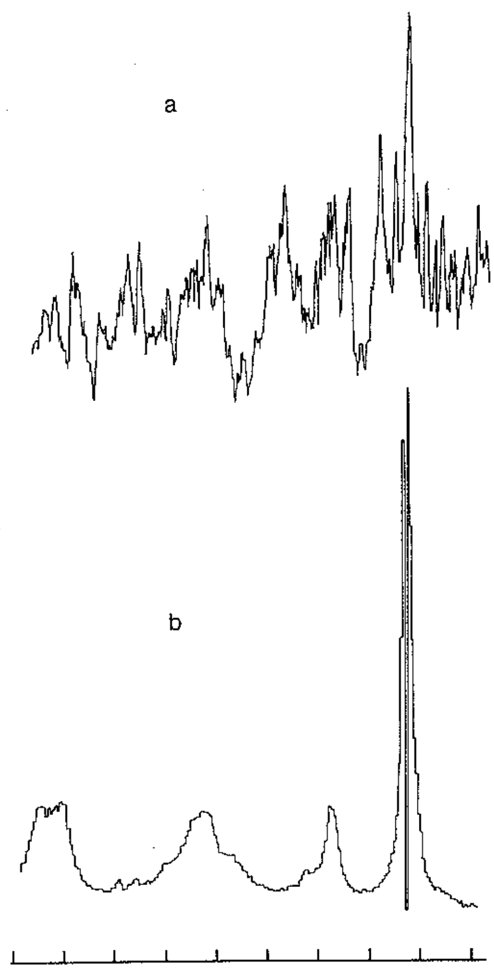


Fig 13 Raman spectrum of tetrahydrofuran (a) uncompensated for laser intensity fluctuations and (b) the same spectrum compensating for laser fluctuations with the PC/DC feature of the DPC-2. Also note the "wrap-around" effect on the highest spectral line.

Table 2
DPC-2 SPECIFICATIONS

Panel Display: Four-digit; switchable to high voltage, output, or test
Pulse Input: TTL pulses 50 Ω impedance
External DC Input: 0 - 50 μA
Reference Pulse Input: TTL pulses, 1 MHz max
Discriminator Output: TTL pulses from preamp
Analog Output: 0 - 100 mV, linear or log presentation,
0.01 - 100 sec smoothing constant (linear)
Digital Outputs: TTL-compatible; accumulated counts to computer on 4 lines;
BCD bit-parallel, character-serial, max 10^9-1; count rate for other
external devices: 16 lines, BCD parallel
Auxiliary Output: TTL-compatible pulse to signal end of each count interval
Photon-Counting Mode:
- Count Rate Accuracy: 96% at 1 million counts/sec
  80% at 5 million counts/sec
- Drift: 0.01% plus 0.3% of any zero suppression
- Accuracy: 0.1% plus 0.3% of any zero suppression
- Zero Suppression: 0 - 500 and 0 - 50000 counts /sec continuously adjustable;
  1-4 decades by truncate or wrap-around
- High Voltage: 100 - 2000 V, negative, front panel adjustable
- Full Scale: 100, 200, 500, 1K, 2K, 5K, 10K, 20K, 50K, 100K, 200K, 500K,
  1M, 2M, and 5M counts/sec (to 50M counts with preamp's prescaler)
- Integration Time: 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100, 200, and 500 sec

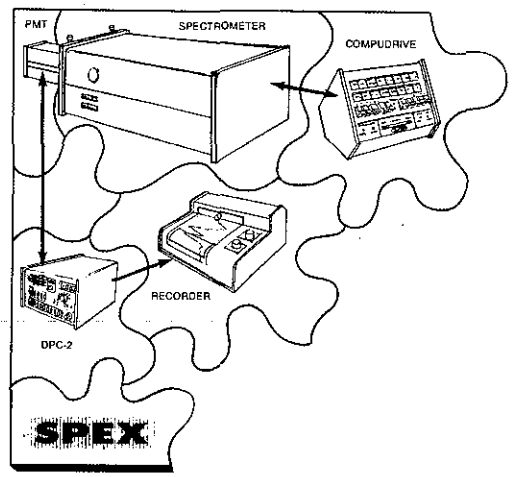
Direct Current Mode:
- Linearity: 0.5%
- Drift: 0.5% per hour (after initial warm-up) plus 0.3% of any zero suppression
- Accuracy: 1%
- Zero Suppression: 0 - 0.5 μA
- High Voltage: 100 - 2000V, negative, front panel adjustable
- Power at HV: Lesser of 2W or 1.5 mA times voltage
- Full Scale: 10, 20, 50, 100, 200, and 500 nA; 1, 2, 5, 10, 20, and 50 μA
- Integration Time: 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100, 200, and 500 sec

General

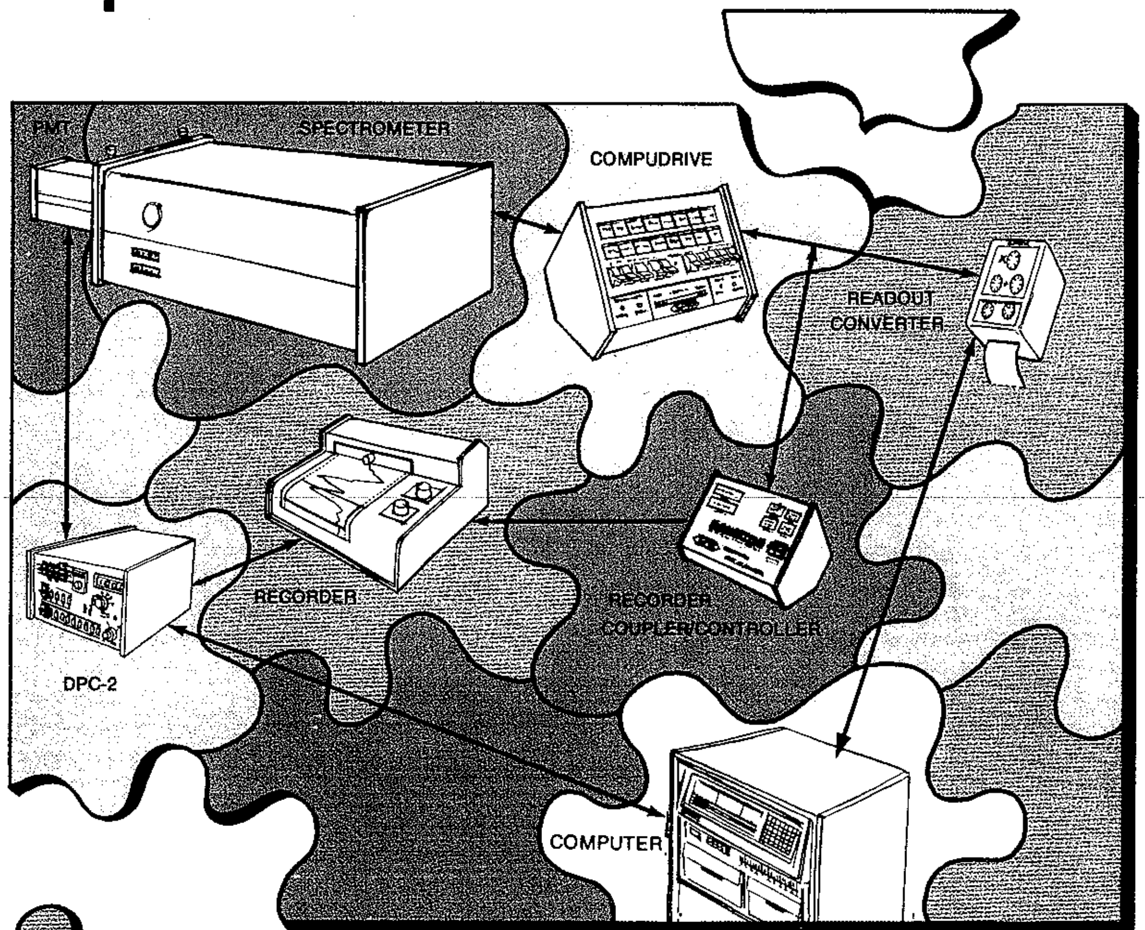
Input Power	115 ± 10% Vac, 50/60 Hz, 1 A
Dimensions,	14 x 22 x 44 cm
Weight	10 kg

REFERENCES

1. W.A. Baum, Astronomical Techniques, Ed W.A. Hiltner, University of Chicago Press (1962), p. 1.
2. R.C. Harney, F.P. Milanovich, Rev. Sci. Inst. **46**, 1047 (1975)
3. F.P. Schwarz, H. Okabe, Anal. Chem. **46**, 1024 (1974)
4. P.J. Layboun, J.P. Dakin, W.A. Gamblin, J. Opt-elect. **2**, 36 (1970)
5. W.M. Moller, J. Chem. Phys. **59**, 2760 (1973)
6. M. Pope, J. Burgos, N. Wotherspoon, Chem. Phys. Lett. **12**, 140 (1971)
7. R.R. Alfano, N. Ockman, J. Opt. Soc. Am., **58**, 90 (1968)
8. M.K. Murphy, S.A. Clyburn, Claude Veillon, Anal. Chem. **45**, 1468 (1973)
9. G.A. Morton, Applied Optics, **7**, 1 (1968)
10. H.V. Malmstadt, M.O. Franklin, G. Horlich, Anal. Chem., **44**, 63A (1972)
11. THE SPEX SPEAKER, Vol. XXI, No. 3 (1976)



Putting together a digital spectrometer system is no puzzle...



SPEX has the pieces to complete the picture

Take one tight annual budget and mix with one or more Spex modular units to yield an efficient, versatile system that will never develop growing pains.

Each of our digital electronic components for system control and data processing will stand on its own and go right to work for you. Each will also interact with photomultiplier tubes, recorders, data handlers, and computers.

SPEX INDUSTRIES, INC./P.O. BOX 798/METUCHEN, N. J. 08840/☎ (201) 549-7144

BULK RATE/U.S. POSTAGE
PAID
PERMIT No. 123
PLAINFIELD, N.J. 07060