

**Development of a Photon Counting System for  
Differential Lidar Signal Detection**

**Final Progress Report for NCC-1-219**

**Submitted to**

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Photon counting has been chosen as a means to extend the detection range of current airborne DIAL ozone measurements. Lidar backscattered return signals from the on and off-line lasers experience a significant exponential decay. To extract further data from the decaying ozone return signals, photon counting will be used to measure the low light levels, thus extending the detection range. In this application, photon counting will extend signal measurement where the analog return signal is too weak.

The current analog measurement range is limited to approximately 25 kilometers from an aircraft flying at 12 kilometers. Photon counting will be used to exceed the current measurement range so as to follow the Mid-latitude model of ozone density as a function of height.

This report describes the development of a photon counting system. The initial development phase begins with detailed evaluation of individual photomultiplier tubes. The PMT qualities investigated are noise count rates, single electron response peaks, voltage versus gain values, saturation effects, and output signal linearity. These evaluations are followed by analysis of two distinctive tube base gating schemes. The next phase is to construct and operate a photon counting system in a laboratory environment. The laboratory counting simulations are used to determine optimum discriminator setpoints and to continue further evaluations of PMT properties. The final step in the photon counting system evaluation process is the compiling of photon counting measurements on the existing ozone DIAL laser system.

### **The Photon Counting System**

Photon counting utilizes the unique characteristic of a photomultiplier tube's ability to detect single photon events. In this mode of detection, photon events are isolated at the anode of

the photomultiplier then counted by a scaler. Employing this method will allow for extended range measurement of atmospheric species whose signals are below the level of analog detection. The photon counting experimental setup is shown in Figure 3.1 and an explanation of individual components follows.

### Photomultiplier Tubes

Two end-window PMT models were used for performance evaluations. THORN EMI series models 9214Q and 9817Q were chosen for their high gain, high speed, dynamic range, signal linearity, and well defined single electron resolution. The Q notation is used to indicate that a fused-silica end window is incorporated as opposed to a borosilicate glass end window. Both PMT models relied on the quartz end window for extended ultraviolet light response.

### Preamplification

Preamplification of the PMT's pulsed output is necessary for discriminator analysis. The output of the PMT is typically in the low millivolt range and of several nanosecond pulse width for single photon events. Amplification of such signals requires the amplifier to have low signal attenuation, low noise, high bandwidth, and fast time response. Two amplifiers were analyzed: the Phillips Scientific Model 6950 DC-300 MHZ non-inverting bipolar amplifier with a voltage gain of ten and the Stanford Research Systems Model SR445 DC-300 MHZ non-inverting fast preamplifier with a voltage gain of five per channel, where up to three channels may be cascaded. Both amplifiers provided acceptable operating characteristics. Preference of either amplifier depends on the total signal amplification desired. An advantage of the SR445

preamplifier was that it allowed for microvolt calibration of its input and output connections to remove any unnecessary bias amplification. In the experiments described the Phillips Scientific preamplifier was used.

### Discriminator

The output from the PMT and preamplifier is a sum of signal and noise pulses. To isolate the lidar signal return, it is necessary to remove the noise pulses efficiently and to minimize signal losses. A Phillips Scientific 300 MHz discriminator is used to remove the noise pulses which also result in improving the system's signal-to-noise ratio (SNR). The noise pulses are removed by determining the optimum setting of the discriminator's threshold level that will discriminate against the noise pulses but record the photon generated pulses. This maximizes the SNR. The threshold level could be varied over a range of -10 mV to -1 Volt by a potentiometer, with the operating level determined by experimentation to be discussed in the Chapter 4. The output of the discriminator is used to drive the computer-controlled pulse counting multichannel analyzer. The pulsed output of the discriminator is based on NIM logic into 50 ohms. The discriminator output pulse width could be adjusted from 2 nsec to 50 nsec. Pulse width adjustment is necessary to minimize the occurrence of pulse pile-up error.

### Multichannel Analyzer

A DSP Technology Inc. Model 2190 Multichannel Averager (MCA) is used to count and sum the pulsed output from the discriminator. A MCA divides the incoming signal into time segments (bins) called dwell periods. The sum of all the dwell periods, specified by a

programmed record length, is equal to one scan or sweep. The total number of sweeps is controlled by programmed input. The Model 2190 functions by counting the number of incoming discriminator pulses during a specified dwell period. The counts are then added to the sum of previous counts made which correspond to dwell periods of previous scans. The end sum is the total number of counts for each dwell period. The MCA is synchronized with the PMT gate signal by an external trigger provided by the pulse generator. A clock signal, produced by a separate function generator, controls the MCA dwell time period normally set at 1  $\mu$ sec. The record length set for expected lidar returns is normally 300  $\mu$ sec (300 dwell periods).

The Model 2190 is physically composed of two interconnected modules, Model 2090S and Model 4101. The Model 2090S is a high speed scaler capable of counting at up to a 100 MHZ rate and a maximum count of 65,535 (16 bits). The Model 4101 is a high speed averaging memory module. The basic operation of the two models is as follows: 1) The 4101 is programmed for the number of data sweeps, the number of dwell periods per sweep (or information data bins), and its memory is reset. 2) The 2090S is then enabled for counting. 3) The 4101 receives a 30 Hz trigger signal and then enables dwell clocks to latch data in the 2090S. 4) After each dwell clock, data is transferred and added to previous data in the 4101 memory. 5) After the programmed number of dwell periods have been cycled, one sweep is completed. When the programmed number of sweeps (see above) has been completed, the 4101 stops for readout over the CAMAC controller.

### Computer and CAMAC Interfaces

The CAMAC interface crate controller provides the means, through digital control, to

send or receive commands or data from individual CAMAC modules to an external computer. A 486 computer provided the necessary control of the CAMAC modules and data output with the addition of a general purpose interface bus (GPIB) module. The GPIB controlling software used was a NI-488.2 MS-DOS standard. The user control software was a Visual C++ program modeled by the MCA basic operation procedure previously outlined. Photon counting data is stored in a computer file for information analysis.

### **Photomultiplier Tube Measurement System**

A PMT measurement and evaluation system was constructed and is shown in Figure 2. Such a system is necessary for accurate and controlled PMT evaluation. Testing under known conditions ensures proper PMT response during field ozone airborne measurements and minimizes operating uncertainties. The system components will now be discussed in detail.

#### Xenon Lamp Light Source

PMT evaluation requires a wide dynamic range of light of variable intensity and wavelength. The light source used for PMT evaluation is shown in Figure 2. A 1000 W xenon lamp is housed inside a forced air cooled lamp housing. The forced ventilation provided cooling for the high pressure lamp as well as removal of ozone produced from operation of the xenon lamp. The lamp housing also provided an adjustable rear reflector coated for maximum ultraviolet reflectivity. A 57 mm condenser lens consisting of two plano-convex elements was placed in the lamp housing's optical axis for beam focusing adjustments.

Power to the xenon lamp was provided by an arc lamp DC power supply. The xenon

lamp's power supply was adjusted to 25 amperes DC and 20 volts DC once the arc lamp power supply had reached operating conditions. The arc lamp DC power supply was also coupled with an optical feedback amplifier aligned with the lamp housing's optical axis. The optical feedback amplifier function is to establish the xenon lamp's output against noise due to arc wander, mechanical vibration, and voltage line ripple. The optical amplifier provides stability under 0.1% ripple to the xenon lamp.

Light from the xenon lamp is directed into a high intensity grating monochromator. The grating used provided a wavelength range of 180 to 800 nm displayed on a three digit counter in increments of 0.2 nm. Entrance and exit variable slit assemblies attached to the monochromator provided for slitwidth control between 0.01 to 6.00 mm displayed in 0.01mm increments. An integrated stepper motor drive system provided for precise wavelength location.

### Detector Box

PMT testing is accomplished by exposing a PMT to light under controlled conditions. Evaluation is performed using a light-tight box which supports two manual shuttered housings on which a PMT housing may be mounted. One manual shutter is aligned directly with the optical path of the xenon lamp. The other manual shutter is offset at an angle of 90° from the optical axis. The inside walls of the light-tight box are of anodized aluminum which are used to isolate a horizontal optic table. The optic table is used to accommodate various optic mounts and devices (neutral density filters, beam choppers, etc.).

### Pulse Height Analyzer

A pulse height analyzer (PHA) was integrated into the photon counting system in order to investigate the pulse height distribution of individual PMT's. A Canberra Series 10 Portable Multichannel Analyzer was used to read the PMT's pulse height distribution which was recorded and printed out. A simplified pulse height distribution is shown in Figure 3. The figure illustrates three distinct regions in the pulse height distribution. Region A is the result of inherent circuit noise, secondary emission from dynodes, and some single electron events. The distribution of Region B is due to single photon to single electron conversion which occurred at the photocathode. Region C defines PMT response to cosmic radiation, radioactive contaminants in tube materials, and effects of after pulsing. This analysis provided the required discriminator threshold settings by determining which pulse height values isolated the single electron response region from the inherent circuit noise.

We will discuss the experimental results obtained from the setup previously described. Selected PMTs were evaluated to establish noise and saturation count rates, cathode voltage operating ranges that yielded constant signal-to-noise ratio, and linearity performance characteristics. Photon counting experiments were then conducted to identify setpoints for the discriminator's voltage threshold and pulse width that would maximize each PMT's linear operating region. Once these measurements were completed, holdoff characteristics of the focus grid and four dynode gating designs were conducted and discussed. Final measurements taken were that of actual photon counting results utilizing the lidar ozone detection system and comparing these results to those attained by the analog measurement method.



## **Photomultiplier Tube Characteristics**

Photomultiplier tubes of the same series, manufactured under similar conditions by the same manufacture, will still each have different operating characteristics. Therefore, individual analysis of photomultiplier tubes is required for the proper determination of their operating characteristics required for implementation in a photon counting system. After an exhausted review of related literature, photomultiplier tube models EMIK 9817Q and EMI 9214Q were selected for photon counting measurements due to their high quantum efficiency in the ultraviolet wavelength spectrum and easy incorporation into the DIAL atmospheric detection system. The tests presented here were conducted to develop an understanding of individual PMT responses and to determine the optimum operating tube characteristics. Uniform PMT current gains were selected to allow for PMT comparisons from the gathered experimental test results. Tube gain was set by the respective PMT cathode voltage that corresponded to a current gain of  $1.5 \times 10^7$  as read from the PMT's gain versus cathode voltage curve. Evaluation of PMT current gains and quantum efficiencies were performed by Burle Industries. Photomultiplier test results have been summarized and are listed in Table 4.1.

## Noise Count Rates

Measurements of PMT noise counts in the photon counting system were performed to identify the amount of noise introduced into the counting system by operation of the PMT detector. The insertion of a PMT from its protective storage container into the PMT base socket and magnetic shielding resulted in short term exposure to ambient light.

### Saturation Count Rate

Examining PMT saturation effects are necessary in order to develop an understanding of the tube's operating limits. Understanding of PMT operation is needed to ensure linear photon counting measurements are taken by the counting system. Saturation of a PMT may be produced by excessive cathode voltages (which causes internal arcing inside the tube) or by exposure to intense incidence light sources. PMT recovery from a saturation condition depends upon the duration and severity of the saturation stimulus and the individual properties of the tube itself.

Saturation effects of PMT were evaluation. The xenon light source was set to 25 amperes and 20 volts DC. Light incident onto the PMT photocathode surface was varied by adjustments of the slit width assemblies. Figure 4 shows the measured increase of count rate corresponding to increased light exposure. It is also noted that as the applied PMT cathode voltage is increased an expected increase in count rate also occurs due to the increase of current gain amplifying more noise. As the intensity of light is increased the PMT count rates begin to experience a decrease and eventual roll-off. Photon counting measurements taken at these levels of light exposure would lead to nonlinear responses and should be avoided. As the cathode voltage is increased, saturation of the PMT occurs at lower light intensities due to the increased PMT current gain. All of the PMTs examined produced similar saturation effect responses.

### Signal-to-Noise Ratio

Photon counting analysis of the PMT's signal-to-noise ratio (SNR) is necessary in order to identify the PMT cathode voltage range that produces the maximum SNR. Using the experimental setup shown in Figure 2, photon counting measurements of signal count rate and

dark count rate were taken for a set PMT cathode voltage (at constant 300 nm light intensity). Calculation of the SNR was performed by dividing the measured signal count rate by the measured dark count rate. The selected cathode voltage range for signal-to-noise analysis was covered in increments of 25 volts. The PMT count rate, dark count rate, and SNR results were plotted as shown in Figure 5.

The SNR measurements were used to isolate the respective PMT cathode voltage operating values that produced linear count rates and yielded maximum detector SNR values. The linear count rate in Figure 5 extends from 1175 to 1475 cathode volts. In this cathode voltage range the corresponding dark counts have a linear response as well. After 1475 volts, dark counts increase nonlinearly and photon counting in this region would lead to unsatisfactory SNR results. Cathode voltage ranges of PMTs that yielded linear SNRs evaluated in the experimental system setup are listed in Table 4.

### Photomultiplier Tube Linearity

Linearity analysis of the pulsed output of a PMT is necessary to verify proper photon counting system operation and to ensure linear PMT output. As seen in Figure 6, if a PMT is exposed to low light intensities at relatively high cathode voltages, significant nonlinearities can be introduced at relatively low PMT output values. The desired PMT linearity response is shown in Figure 7. At a voltage output of two volts from the PMT and amplifier, the slope and signal change during the gated-on period should be negligible. These requirements are desired because of the differential nature of the lidar DIAL measurement.

Linearity measurements were conducted using the experimental arrangement shown in

Figure 2. The amplifier output was connected to a 50 ohm load on a digitizing oscilloscope used to display the 1000 sum averaged data of the PMT output. The voltage output of the PMT with amplifier was controlled by varying the light intensity incident on the PMT. Once the desired voltage output was attained (2 volts), the PMT with amplifier output was averaged and printed out for hard copy analysis. The slope and signal change of the voltage outputs were calculated and listed in Table 1. The measured PMT output signal changes were quite low and are desired for the DIAL measurement technique. Due to the individual operating characteristics of the PMTs, there was no clear operating linearity difference between the EMI 9214Q and EMI 9817Q series. PMTs EMI 9214QB #5162 and EMI 9817QA #3236 produced the best linear response during the gate on period.

**Acknowledgment:**

This work was performed at NASA by Brad Eccles as part of his MS thesis.

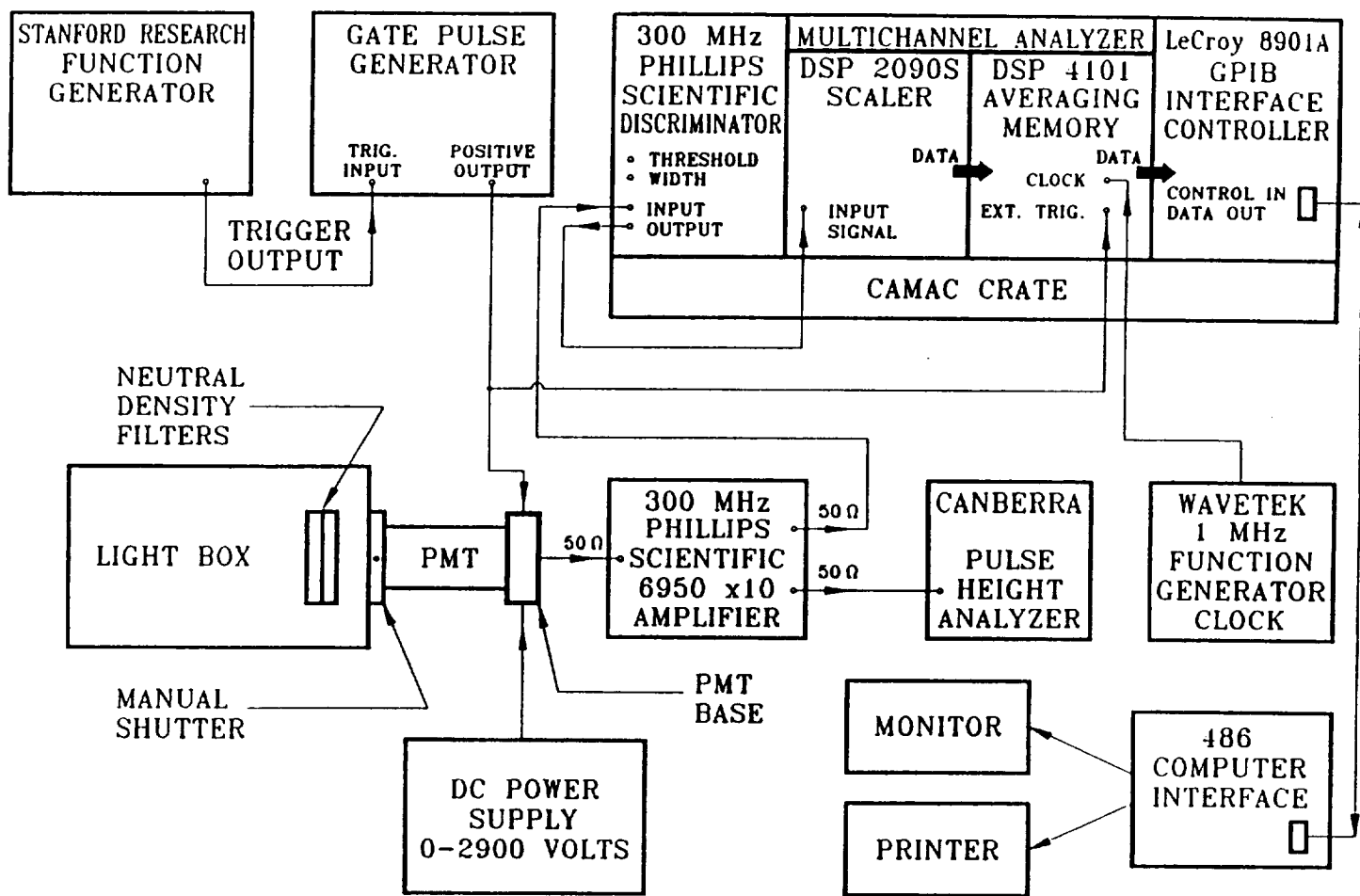


Figure 1. Photon counting experimental setup.

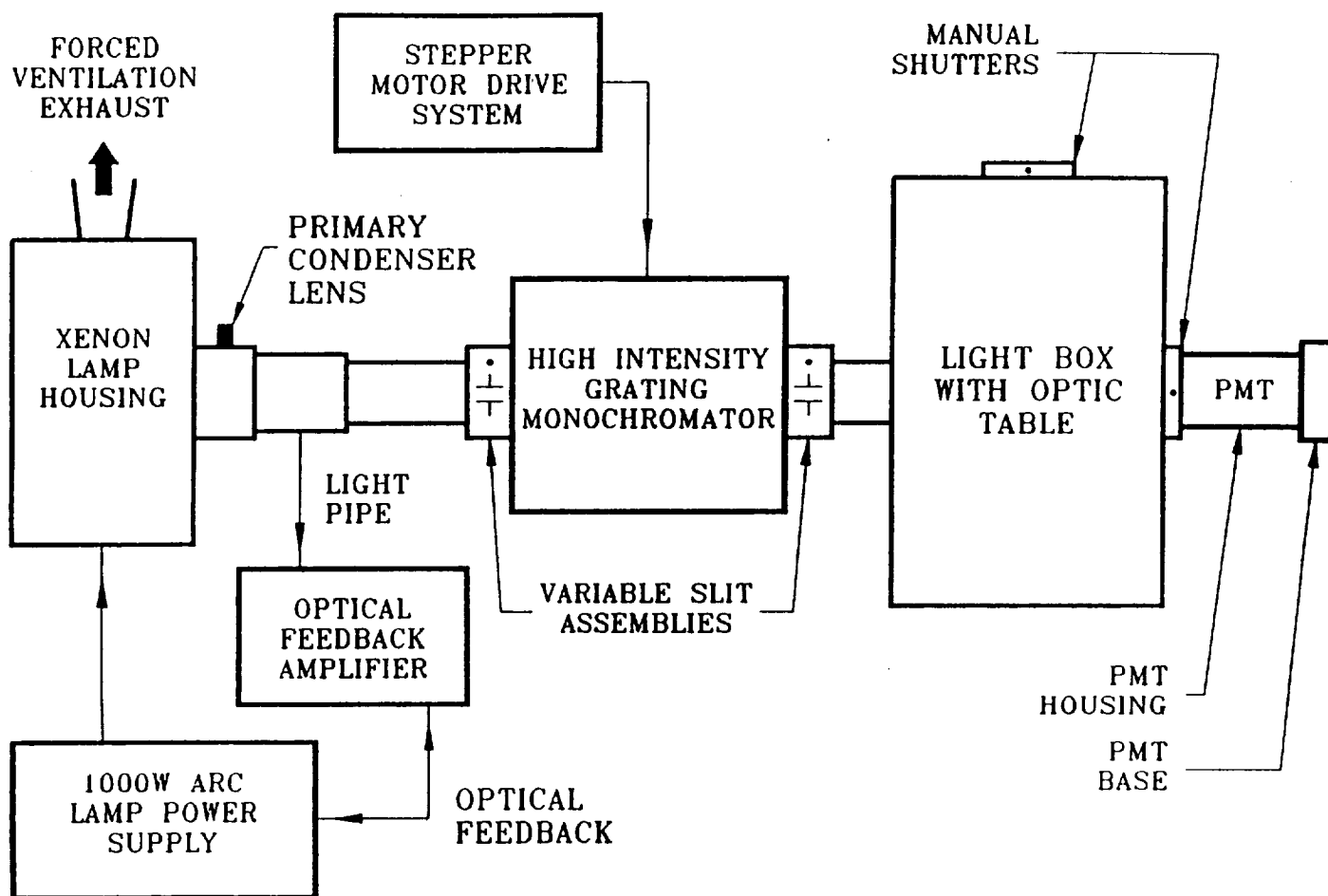


Figure 2. Light source schematic utilized for photomultiplier tube evaluation.

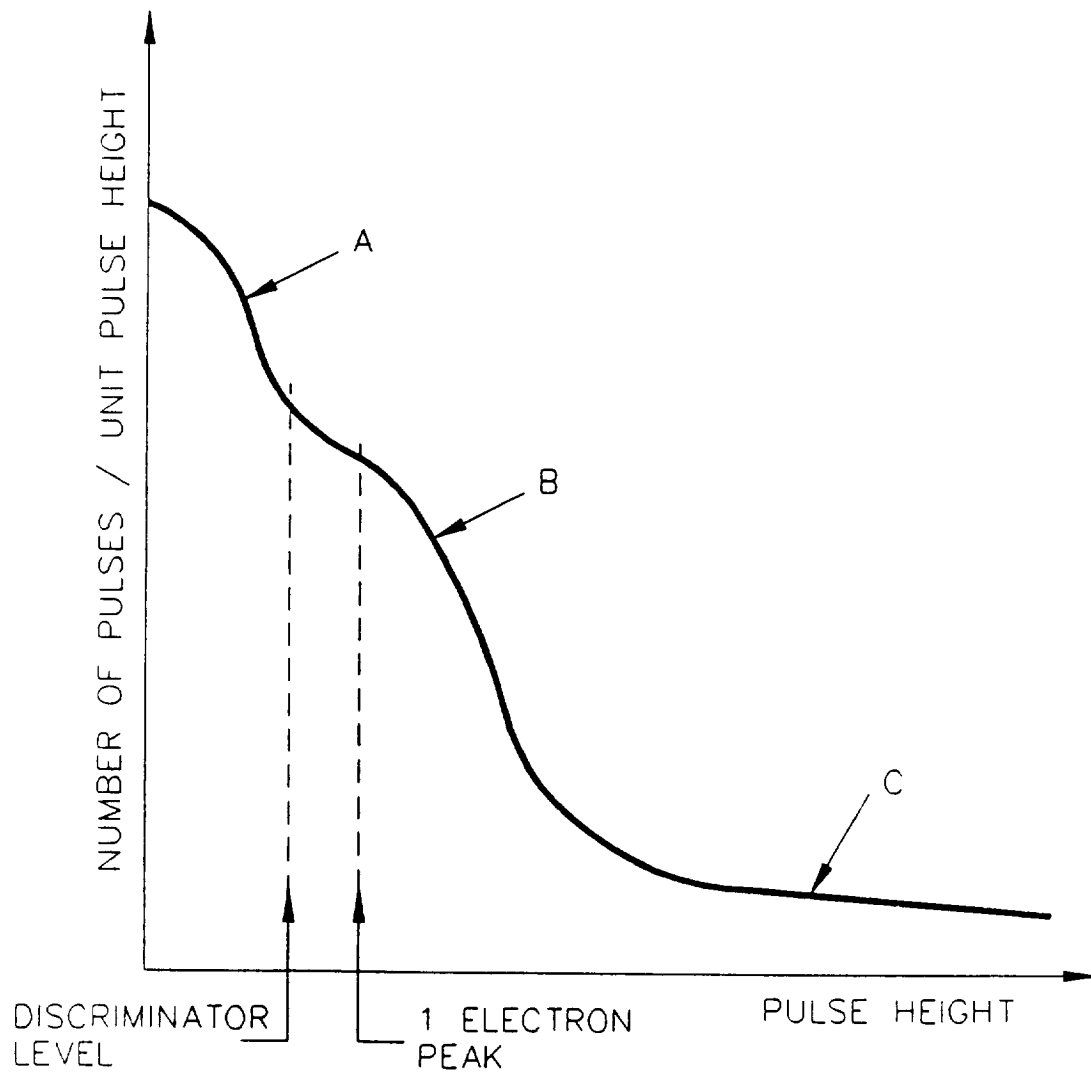


Figure 3. A simplified pulse height distribution for desired discriminator pulse height setting.

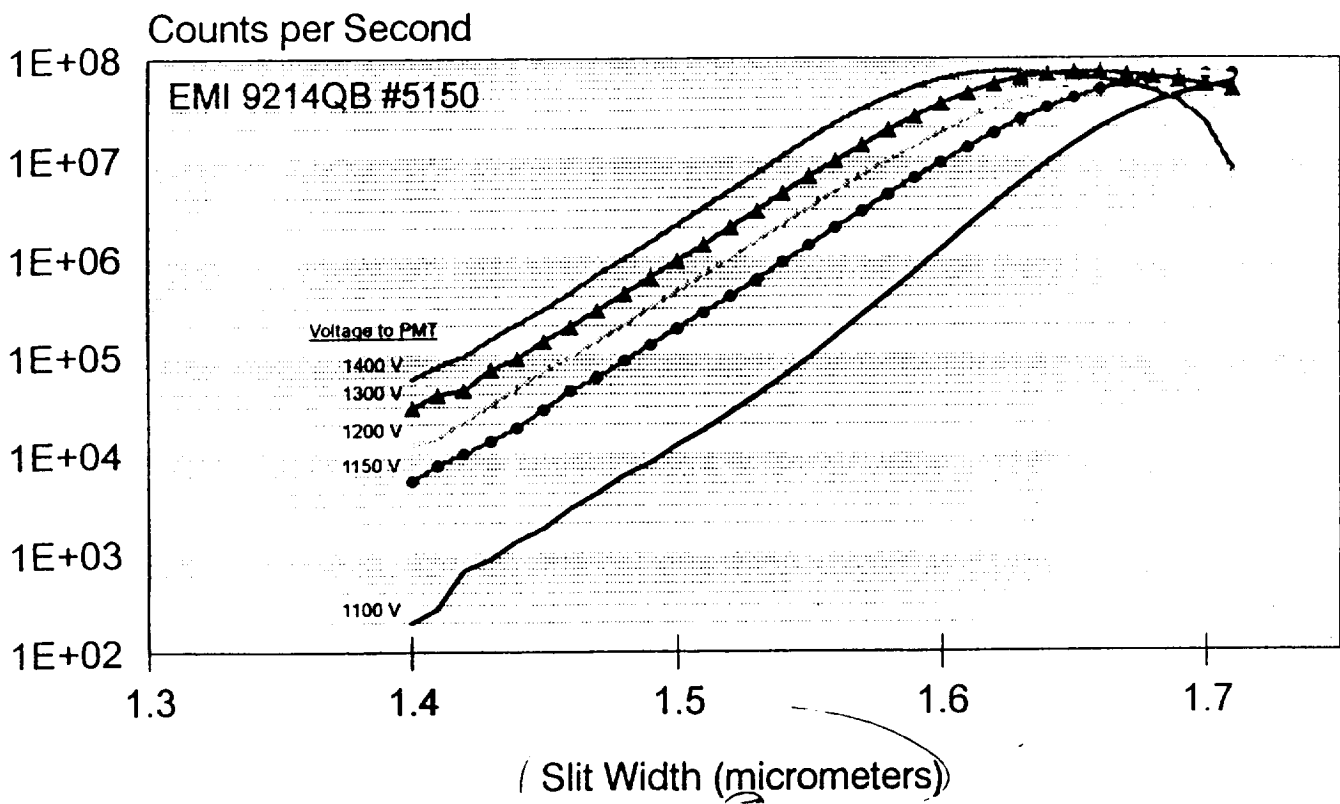


Figure 4. Photomultiplier tube saturation data due to increasing light intensities.



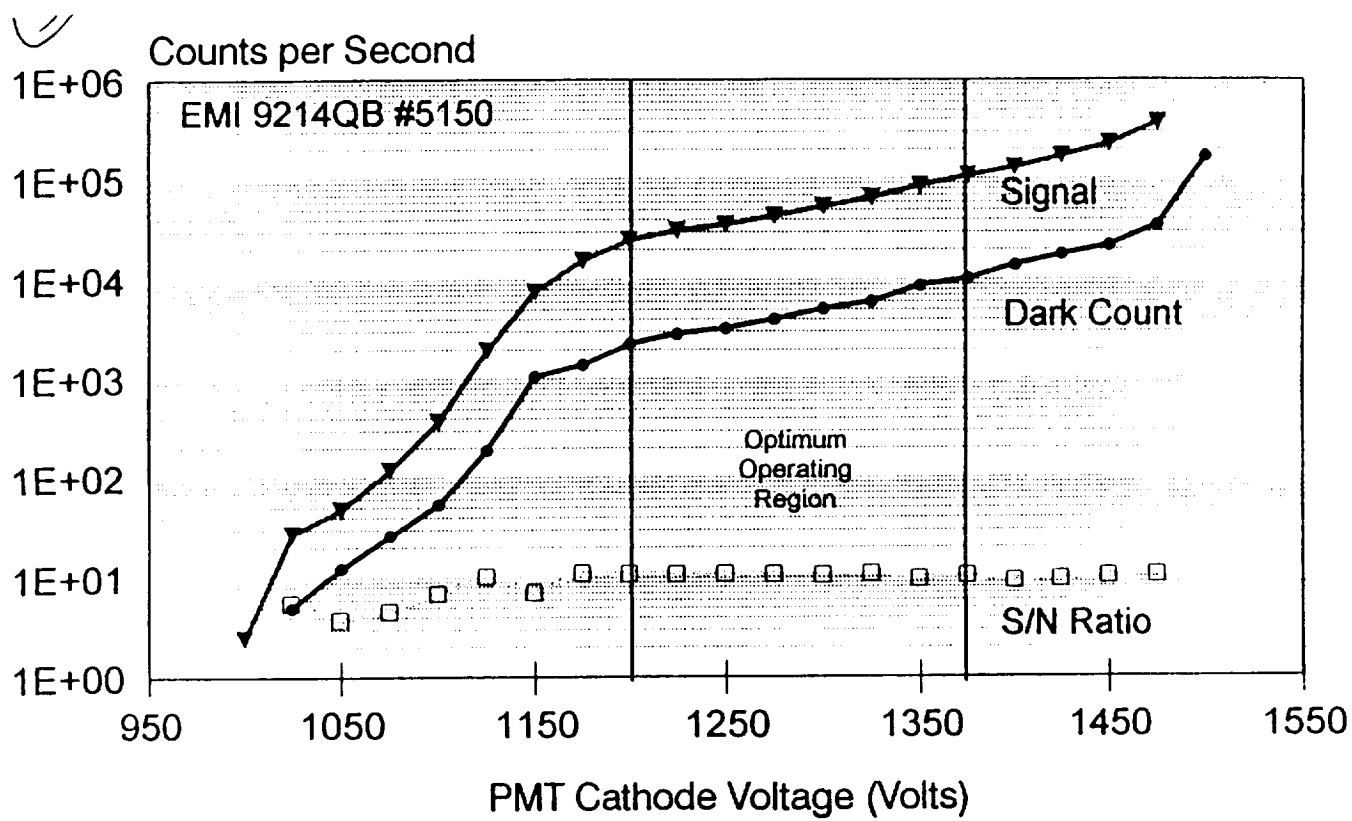


Figure 5. Signal-to-noise results shown with photomultiplier tube count rate and dark count rate.

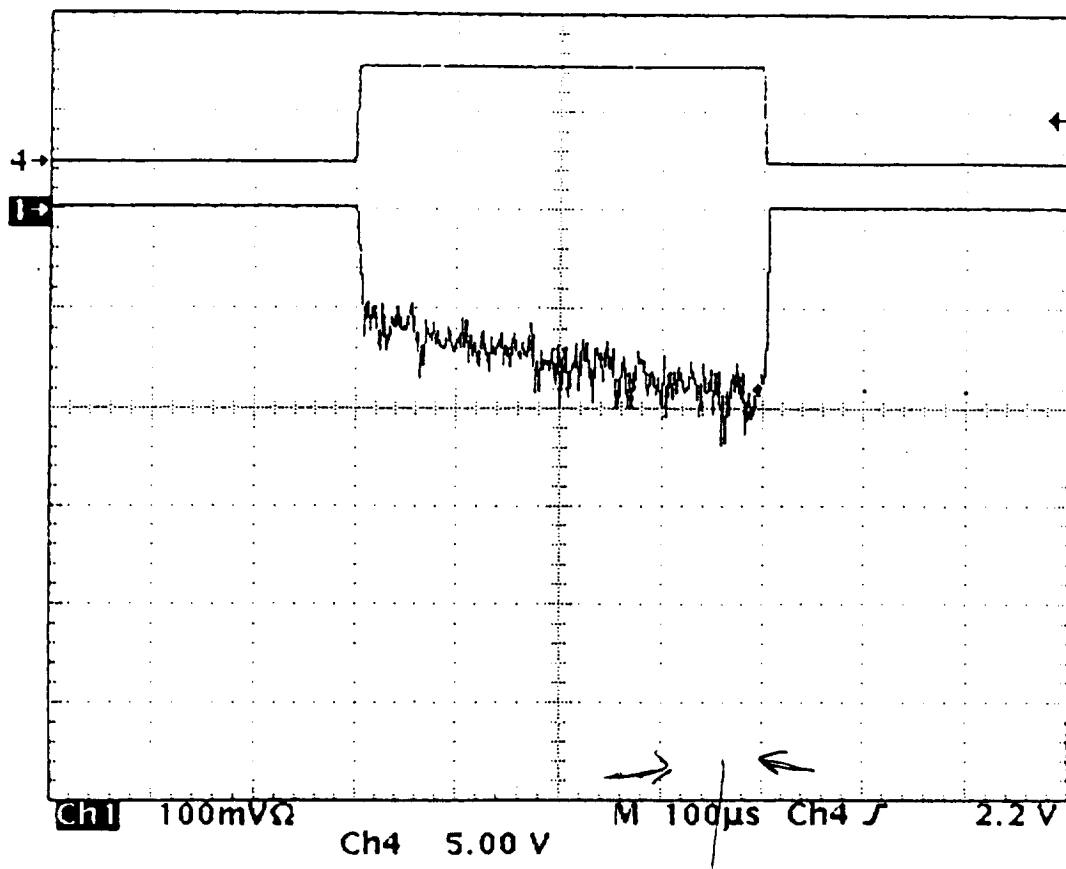


Figure 6. EMI 9214QB #5150 at 1500 volts showing nonlinear output during gate on period. Minimal light exposure. Ch 1: Tube output. Ch 4: Gate signal.

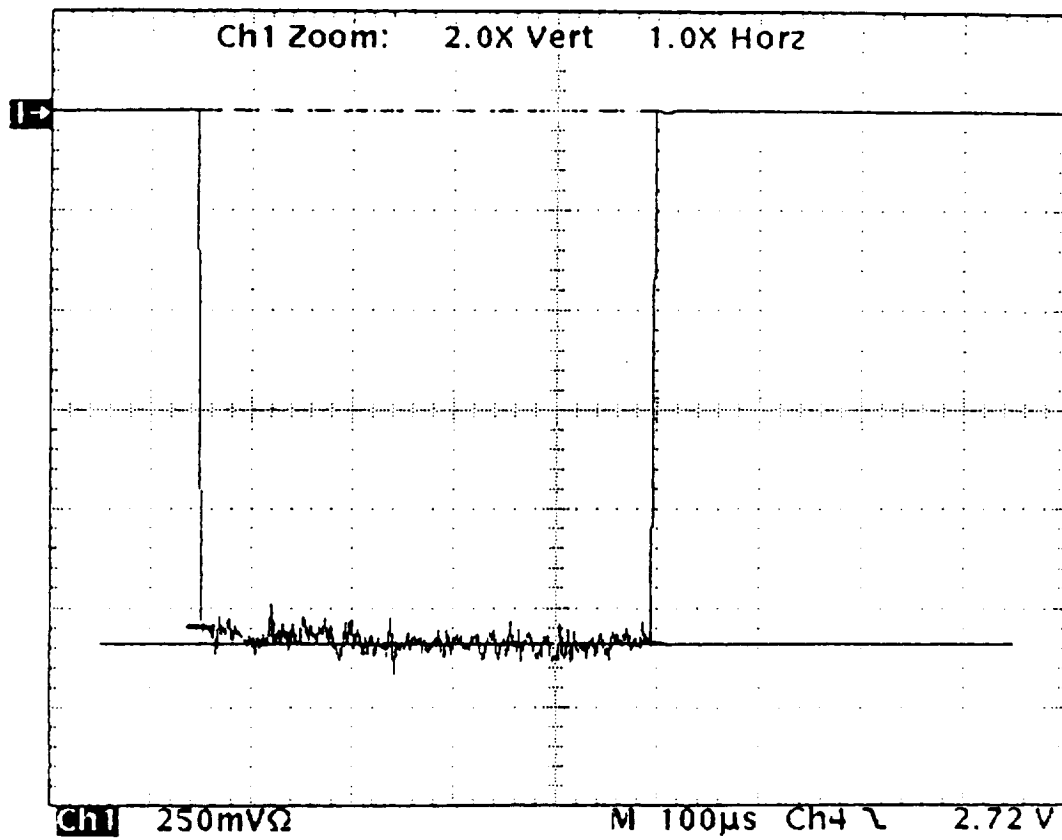


Figure 7. EMI 9817QA #3236 at 2300 volts showing typical linear output. Tube output.

MANUFACTURE SERIAL#	PHOTO- CATHODE MATERIAL	DYNODE CHAIN MATERIAL	QE @ 300 nm (%)	VOLTAGE FOR GAIN OF $1.5 \times 10^6$ (Volts DC)	NOISE @ 70 mV DISCRIMINATOR THRESHOLD (counts/sec)	CONSTANT SNR OPERATING RANGE	SLOPE OF OUTPUT SIGNAL (mV/microsec)	SIGNAL CHANGE DURING GATE ON @ 2 VOLTS OUT (mV)	OPTIMIZED DISCRIMINATOR THRESHOLD @ 30 Hz (mV)	COMMENTS
EMI 9214QA #5156	BIALKALI Sb-K-Cs	CsSb	26.6	1525	16100	1200- 1600	0.22	100	110	
EMI 9214QB #5150	BIALKALI Sb-K-Cs	CsSb	31.5	1300	14950	1175- 1475	-0.28	-130	110	
EMI 9214QB #5162	BIALKALI Sb-K-Cs	CsSb	25.2	1280	16000	1200- 1575	0.07	30	100	
EMI 9817QA #3167	S20 Na-K-Sb-Cs	BeCu	25.2	2670	87500	2300- 2700	-0.54	-250	140	VERY HIGH VOLTAGE FOR GAIN
EMI 9817QA #3233	S20 Na-K-Sb-Cs	BeCu	28.3	2400	209000	2175- 2450	-0.17	-80	150	
EMI 9817QA #3236	S20 Na-K-Sb-Cs	BeCu	23.2	2260	296100	2050- 2400	-0.11	-45	105	
EMI 9817QA #3283	S20 Na-K-Sb-Cs	BeCu	23.6	2070	381600	1950- 2300	-0.37	-170	110	
EMI 9817QA #3285	S20 Na-K-Sb-Cs	BeCu	22.8	2375	254500	2175- 2450	-0.33	-150	105	

Table 1. Photomultiplier tubes used for photon counting.