(NASA-TM-78027) A SYSTEM FOR MEASURING THE PULSE HEIGHT DISTRIBUTION OF ULTRAFAST PHOTOMULTIPLIERS (NASA) 28 p HC A03/MF A01 CSCL 09C

N78-16341

Unclas
G3/35 02495

NASA

Technical Memorandum 78027

A SYSTEM FOR MEASURING THE PULSE HEIGHT DISTRIBUTION OF ULTRAFAST PHOTOMULTIPLIERS

J. B. Abshire

DECEMBER 1977

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

BIBLIOGRAPHIC DATA SHEET

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TM-78027		

4. Title and Subtitle
A System for Measuring the Pulse Height Distribution of Ultrafast Photomultipliers

5. Report Date
December 1977

6. Performing Organization Code
723

7. Author(s)
James B. Abshire

8. Performing Organization Report No.
G7802-F2

9. Performing Organization Name and Address
Goddard Space Flight Center
Greenbelt, Maryland 20771

10. Work Unit No.
506-20-33

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Selected by Author(s))
Photomultiplier measurement systems, High-speed photomultipliers, Sampling Oscilloscope, Static crossed-field photomultiplier

18. Distribution Statement
STAR Category 35
Unclassified–Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	30	$4.50

*For sale by the National Technical Information Service, Springfield, Virginia 22151.

GSFC 25-44 (10/77)

All measurement values are expressed in the International System of Units (SI) in accordance with NASA Policy Directive 2220.4, paragraph 4.

Abstract

A system for measuring the pulse height distribution of gigahertz bandwidth photomultipliers has been developed. This system uses a sampling oscilloscope as a sample-hold circuit and has a bandwidth of 12 gigahertz. Test results are given for a static crossed-field photomultiplier tested with a demonstration system. Calculations on system amplitude resolution capabilities are included for currently available system components.

A System for Measuring the Pulse Height Distribution of Ultrafast Photomultipliers

James B. Abshire

Introduction and Summary

A new system has been developed for measuring the single photo-electron pulse height distribution of photomultipliers with picosecond response times. Although other measurement systems developed for these detectors have been recently described[1], the bandwidth of these systems is currently limited to approximately one gigahertz. (Systems for measuring pulse height resolution of lower bandwidth photomultipliers have been in use for many years.)[2, 3] The new system uses a sampling oscilloscope as a very fast sample-hold circuit and has a measurement bandwidth of 12 gigahertz for high-gain photomultipliers. For lower gain photomultipliers, preamplifiers must be used to amplify the photomultiplier signal above the noise of the sampling oscilloscope. With presently available preamplifiers, the system bandwidth limit is approximately 4 gigahertz.

Measurements of a demonstration system composed of available components show the amplitude sensitivity of the demonstration system to be 0.2 millivolts. With the best available low-noise preamplifiers and low-noise sampling heads, the ultimate sensitivity of a 4-gigahertz bandwidth system is calculated to be limited to 0.05 millivolts.

Test results are presented for a static-crossed field photomultiplier, and show excellent agreement with pulse height distributions measured with other instrumentation systems. With the combination of high bandwidth, high amplitude sensitivity, and good sampling speed, this system should be useful for testing next-generation high speed photomultipliers.

System Description

Figure 1 shows a block diagram of the measurement system. The optical signal source for the system is identical to that described in Reference 1. The optical pulses exiting the variable optical attenuator are very short 0.53 μm pulses, with signal levels of from 1 to 1000 photons. Figure 2 shows the measured shape of the 1.06 μm laser pulses. Since available instrumentation did not permit direct measurement of the 0.53 μm pulse shape, the shape was calculated based upon the measured 1.06 μm pulse shape. These calculations are described in Reference 1. Since the 1.06 μm pulse was broadened by the measurement system prior to being used in the calculations, the calculated 0.53 μm pulse shape shown in Figure 3 is also broader than the actual pulse shape. The actual width of the 0.53 μm pulse is estimated to be 50 picoseconds.

After being illuminated with these short 0.53 μm pulses, the output of the photomultiplier under test is fed to a Schottky-diode pulse limiter. This device protects the sensitive post detection preamplifier from ion-feedback generated

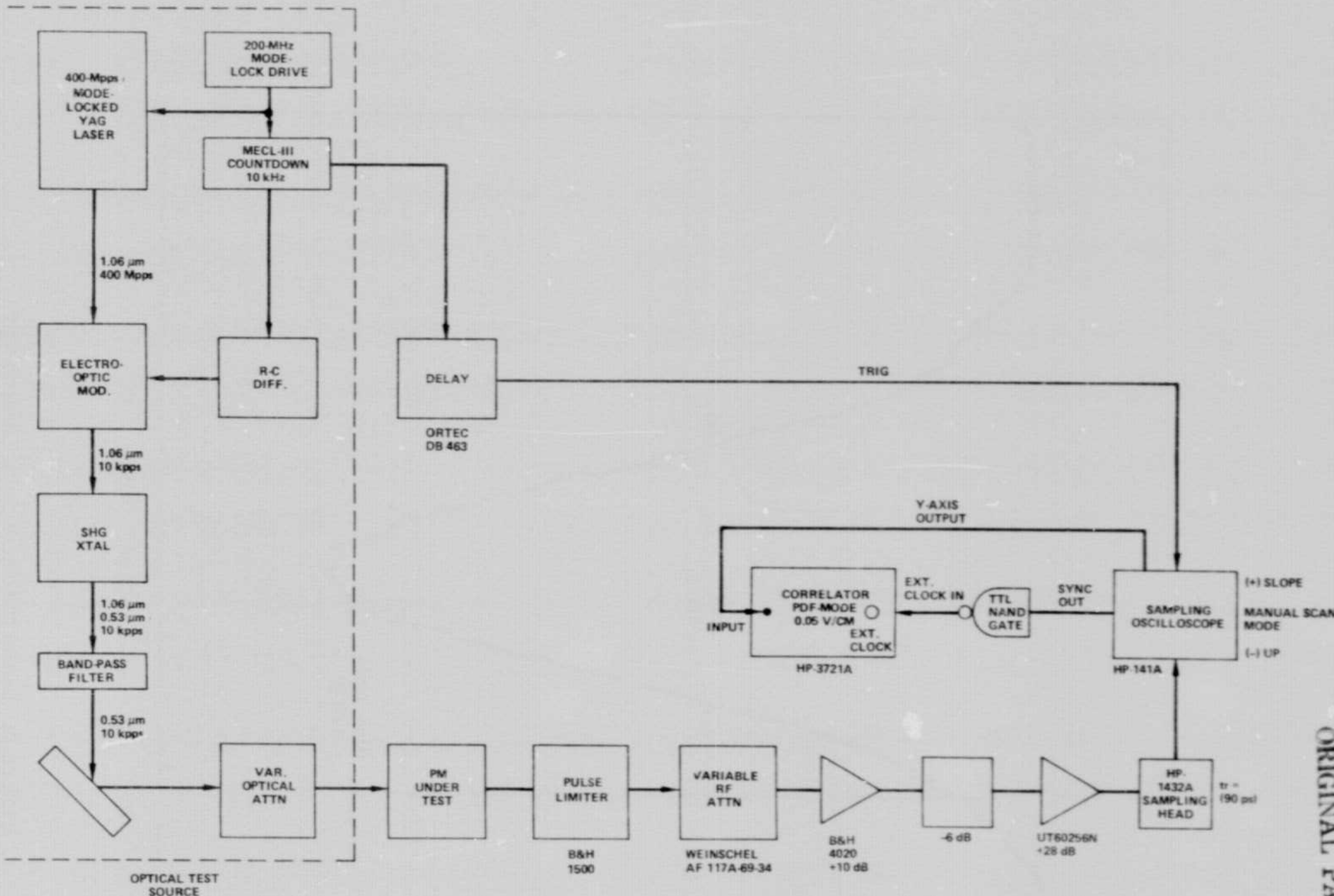

Figure 1. System for Measuring Single Photoelectron Voltage of Photomultipliers Using a Sampling Scope

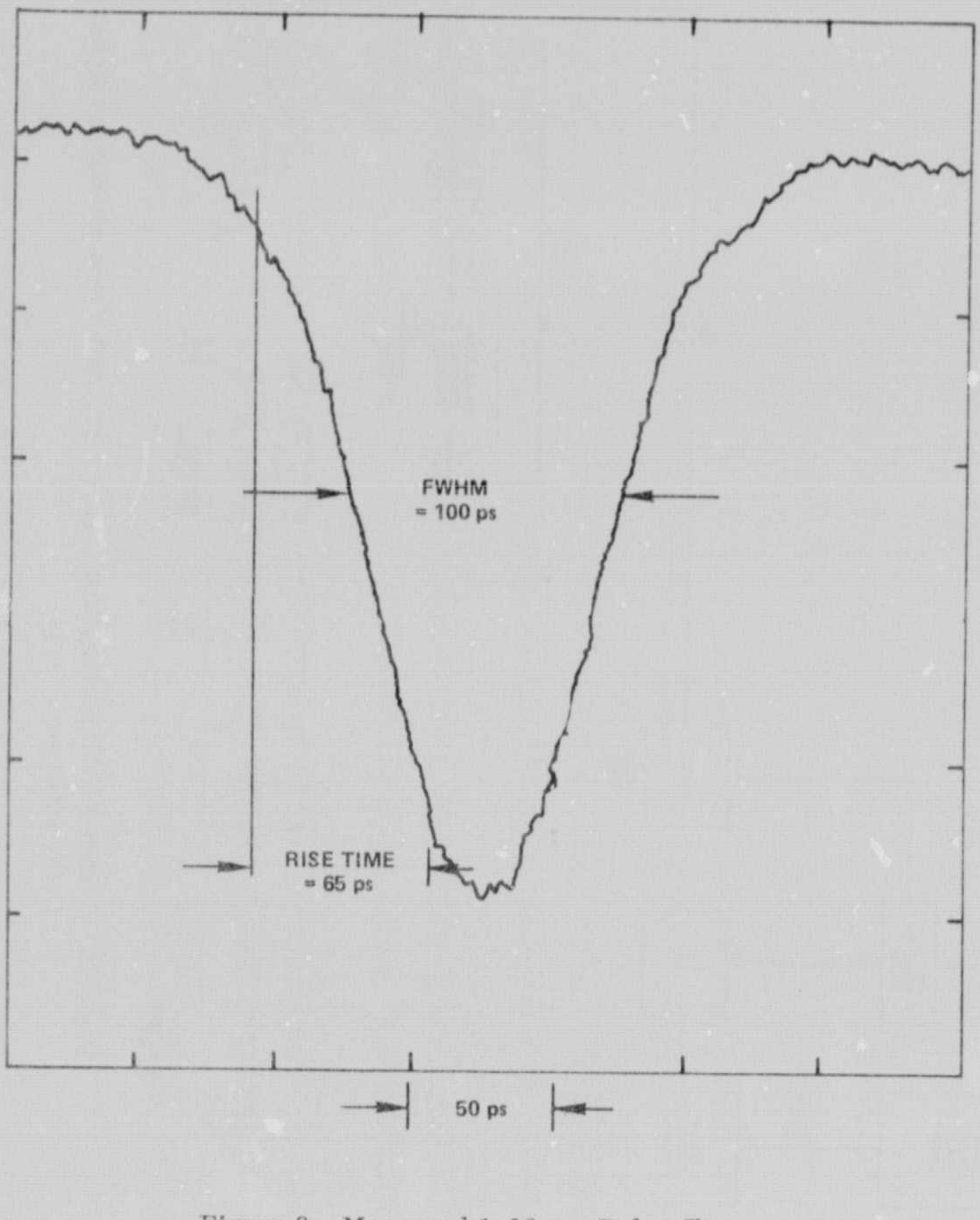

Figure 2. Measured 1.06 μm Pulse Shape

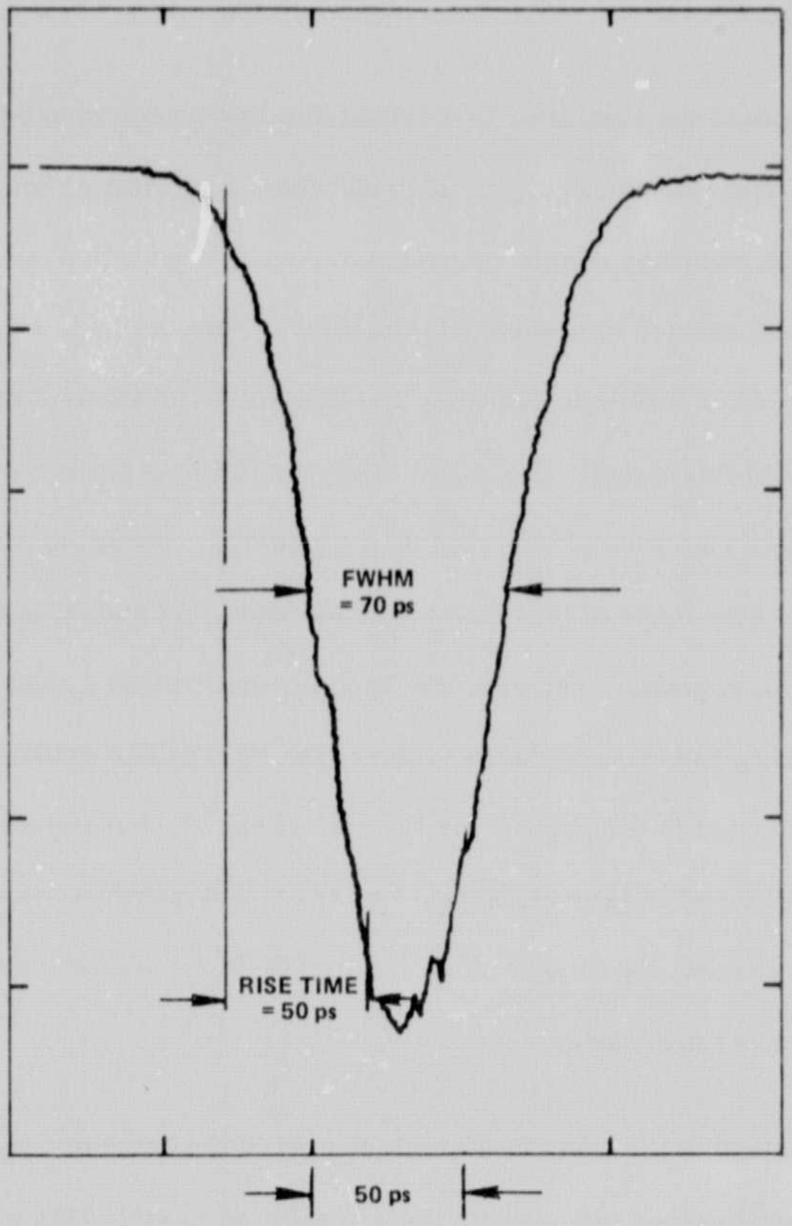

Figure 3. Calculated 0.53 μm Pulse Shape

noise pulses. Pulses with amplitudes of less than 200 millivolts are passed through the limiter undistorted. The output of the pulse limiter goes to the variable RF step attenuator, which has a bandwidth from dc to 18 GHz.

The output of the attenuator is directed to a low-noise, wide bandwidth preamplifier. This device has a gain of 10 dB with a bandwidth of dc to 4 GHz. The output of the amplifier then is connected to a wide bandwidth fixed attenuator, whose output is connected to another RF amplifier. This device has a gain of +28 dB and a bandwidth of 1 MHz to 1.5 GHz, and effectively limits the bandwidth of the amplifier chain to this range. The output of the amplifier is fed to the sampling head, which has a rise time of less than 90 picoseconds. (Sampling heads are available which have rise times of less than 28 picoseconds, but such rise times were not necessary for these tests). The sampling head is connected to a sampling oscilloscope that is triggered by the delayed output of the MECL-III countdown circuit. The delay is adjusted to compensate for the optical and electrical path differences between the signal and trigger channels. For the model oscilloscope used in the demonstration system, the trigger pulse must precede the desired sample time by approximately 120 nanoseconds.

After adjusting the delay to obtain a display of the detector output pulse, the sampling oscilloscope was put into the manual scan mode. This mode permits repetitive sampling of any point on the detector output pulse. By adjusting the scan position to the peak of the waveform, the sampling oscilloscope will sample the peak voltage of the photomultiplier output repeatedly, in synchronism with the laser repetition rate. The analog voltage for each sampled peak voltage is then available at the y-axis output terminal of the oscilloscope until the next sample is taken. A synchronization pulse is also available from the oscilloscope SYNC terminal every time the sampling oscilloscope takes a sample. Since the aperture time of the sampling head is very short, the sampling oscilloscope effectively serves as a very fast sample-and-hold amplifier for the remainder of the circuitry.

The sample-and-hold voltages go to the input channel of a realtime correlator, which is set in the probability density mode. In this mode the correlator functions effectively as a 100-channel multichannel analyzer. For every trigger pulse, the correlator samples and digitizes the analog input. The digital values range linearly from 0 to 100, with increasing channel numbers corresponding to increasing sampled voltages. The correlator has a separate counter for each channel number which indicates the number of times that channel number has occurred. The correlator display shows the number of counts in each channel and thus a histogram of the analog input voltages. Since the input to the correlator was the sampled-and-held value of the detector peak output voltage, the correlator display is essentially a histogram of the detector peak pulse response to the short optical pulses.

By adjusting the optical attenuator, the optical signal level to the photomultiplier can be reduced to a few photons per pulse. At this low signal level the histogram will be dominated by counts at zero volts, which corresponds to zero photoelectrons being emitted from the photomultiplier photocathode. Since the photoelectron occurrences follow a Poisson distribution, any voltages above zero volts with high probability correspond to a single photoelectron emission from the photocathode. By taking a large number of counts in the histogram, a peak in the single photoelectron distribution can be resolved at one particular channel number. From calibrations of the system sensitivity, the most likely single photoelectron voltage from the photomultiplier can easily be determined.

Noise and Bandwidth Considerations

Any noise in the signal path from the photomultiplier anode to the correlator input will add to the anode signal and spread the measured histogram. More precisely, assuming the photomultiplier output and all noise sources to be uncorrelated, the measured histogram is the convolution of the photomultiplier histogram with the histograms of all noise sources. It is therefore important to consider the effects of system noise on measurement results.

The sampling head itself is the major noise source of this system. A histogram of sampling noise for the system is shown in Figure 4 and has an FWHM of 31.5 millivolts. If the sampling noise has a Gaussian distribution,

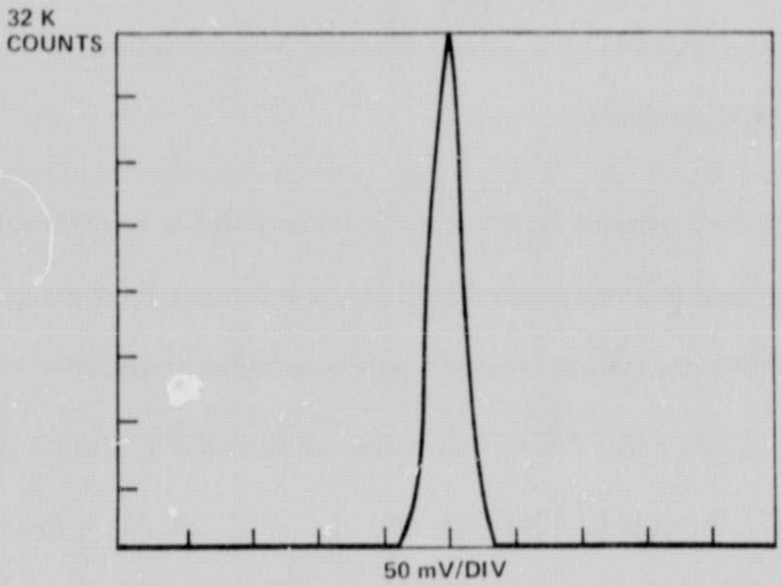

Figure 4. Histogram of Residual Sampling Noise

then this value corresponds to a residual rms noise voltage of 13 millivolts. To measure a single photoelectron peak without using preamplifiers, the single photoelectron voltage must exceed the system noise limit of 31.5 millivolts. If the photodetector has sufficient gain to exceed this voltage, then the system bandwidth is limited only by the bandwidth of the sampling head. Since available sampling heads have rise times of less than 28 picoseconds, the system can measure the single photoelectron distributions of such photomultipliers with bandwidths in excess of 10 gigahertz.

To measure the distributions of lower gain photomultipliers, external preamplifiers must be used to amplify the single photoelectron voltage above the sampling noise. Since the fastest commerically available preamplifiers have bandwidths from dc to 4 GHz, these preamplifiers limit the bandwidth of the measuring system. By using 20 dB of external amplification, for example, the sensitivity of the system can be increased to 3.15 millivolts, but at a cost of degrading the system rise time to 90 picoseconds. This rise time is still slightly faster than rise times of static-crossed field photomultipliers,[4] which are fastest photomultipliers currently available.

Since the residual rms noise of the sampling head is 13 millivolts, a large amount of preamplification can be used with the system to improve the system resolution. The following discussion calculates the limitations in amplitude resolution imposed by preamplifier and sampling noise.

The noise power output of an amplifier with its input port terminated is given by

$$P = KTo\,BGNf \tag{1}$$

where

P = noise power at amplifier output in watts

K = Boltzmann's constant (1.38044×10^{-23} Joules/K)

To = system temperature (293 K)

B = system bandwidth in Hertz

G = amplifier power gain

Nf = noise factor.

The noise factor is defined by

$$Nf = 10^{(NF/10)} \tag{2}$$

where N_F is the amplifier noise figure (dB).

For n amplifiers in series, the effective gain and noise factors are given recursively by

$$G_n = g_n \cdot G_{n-1} \tag{3}$$

and

$$NF_n = Nf_{n-1} + (nf_n - 1)/G_{n-1} \tag{4}$$

where

$$G_o = 1 \tag{5}$$

$$Nf_o = 1 \tag{6}$$

and G_n = effective gain of series combination of n amplifiers

g_n = gain of the n^{th} amplifier

Nf_n = effective noise factor of series combination of n amplifiers

nf_n = noise factor of n^{th} amplifier.

Assuming the sampling noise and the amplifier noise to be independent Gaussian random processes, the system FWHM noise level is given by

$$V_N = 2.36\sqrt{V_S^2 + V_A^2} \tag{7}$$

where

V_S = rms sampling noise voltage

V_A = rms amplifier noise voltage.

The rms amplifier noise voltage is in turn given by

$$V_A = \sqrt{P_o \cdot Z} \tag{8}$$

where P_o = noise power output of amplifier (watts)

Z = system impedence (ohms).

The system amplitude sensitivity is given by

$$R_S = V_N/G_V \tag{9}$$

where

G_V = the voltage gain of the amplifier chain.

By using the above equations, the system FWHM noise level and system sensitivity can be calculated for increasing numbers of amplifiers in the preamplifier chain. A summary of calculations are given in Table I, for a system with 50 Ω impedence, preamplifiers with 10 dB gain, 5 dB noise figure, and 4 gigahertz bandwidth.

As can be seen from this table, no appreciable increase of the system noise level occurs until five stages of preamplification are used. For five stages of amplification, the minimum resolvable signal is 0.157 millivolts, while for six stages, this signal is 0.127 millivolts. Thus, from noise considerations alone, five or more stages of amplification would be desirable to maximize the amplitude resolution of the system. From a practical standpoint, however, other factors must be taken into consideration when using a large number of preamplifiers in series. These factors include both the output power drive capabilities of the amplifiers in the later stages in the chain, and the cumulative effect of pulse distortions by amplifiers with ripples in their frequency response curve. These factors could limit the number of preamplifiers to less than those indicated by system noise considerations.

For the amplifier chain used in the demonstration system, B = 1.6 gigahertz, $G = 2.51 \times 10^3$ and $N_f = 5.7$; therefore, the noise power output of this chain is 0.086 microwatts, and the rms noise voltage of the chain is 2.08 millivolts. The system noise level is calculated to be 31 millivolts FWHM, and the system sensitivity is 0.61 millivolts.

Table I
Sensitivity of Pulse Height Measurement System with Increasing Number of Preamplifiers

Number of Stages	Gain (dB)	Gain (voltage)	Noise Factor	Rms Ampl. Noise (mV)	System FWHM Noise Level (mV)	System Sensitivity (mV)
1	10	3.16	3.16	0.165	30.7	9.72
2	20	10	3.37	0.523	30.7	3.07
3	30	31.6	3.39	1.65	30.9	0.978
4	40	100	3.40	5.23	33.1	0.331
5	50	316	3.40	16.5	49.6	0.157
6	60	1000	3.40	52.3	127	0.127

Test Results

The measurement system described earlier was tested with a Varian 154 A/1.6L photomultiplier. This photomultiplier has been evaluated recently, using the measurement system described in Reference 1. The average impulse response of this photomultiplier is shown in Figure 5, and shows the detector to have 120 picosecond rise time and a pulse height of 160 picoseconds FWHM. The pulse height distribution measured in Reference 4 for this detector is shown in Figure 6, and shows two-photoelectron resolution, with the most likely single photoelectron voltage to be 6.6 millivolts.

Figure 7 shows the results of testing this photomultiplier with the new measurement system. The distribution shows the large peak at 6.6 millivolts, corresponding to one photoelectron, with a very small peak at the two-photoelectron level. The position of the single photoelectron peak is in excellent agreement with that made with the different measurement technique.

Another measurement made with less system sensitivity is shown in Figure 8. This figure also shows the single photoelectron voltage to be 6.5 millivolts and a slight peak at the two photoelectron voltage. Figure 9 shows another measurement of the pulse height distribution, that was made at a slightly higher optical level than those previously shown. The first narrow peak corresponds to one photoelectron, while the second broad peak corresponds to two or

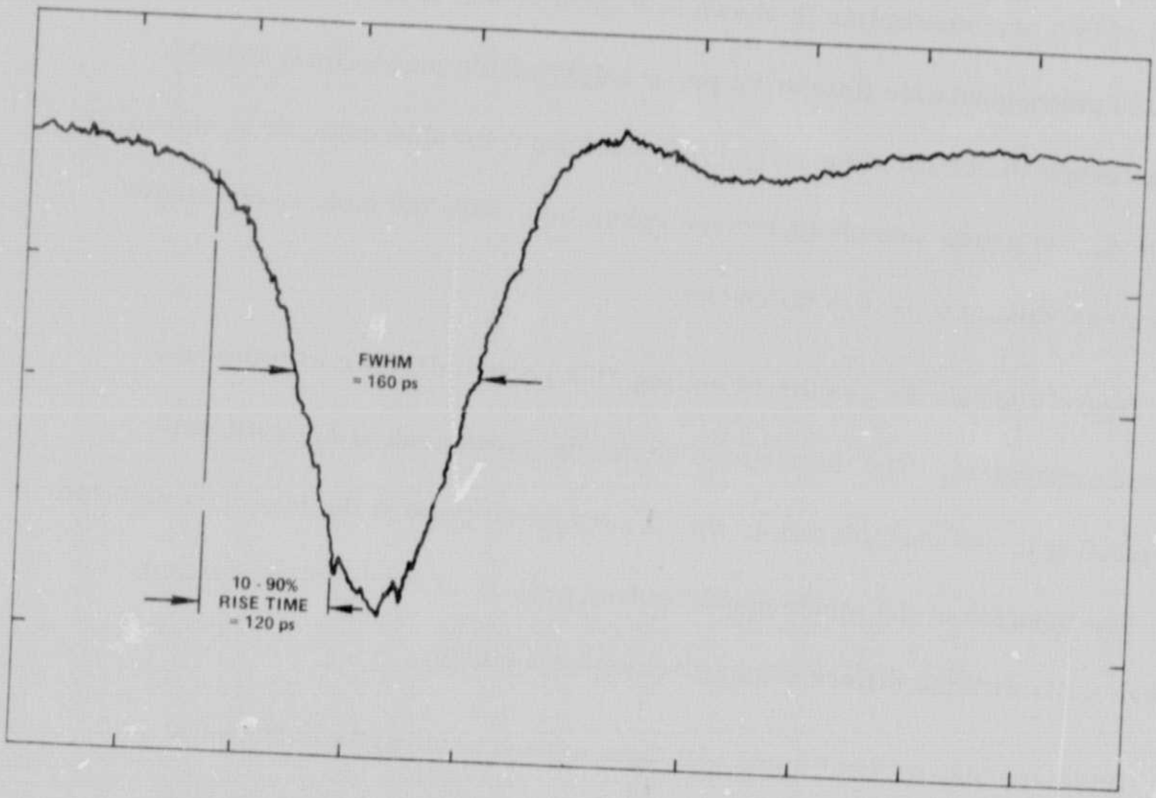

Figure 5. Varian 154 A/1.6L Average Pulse Respcnse

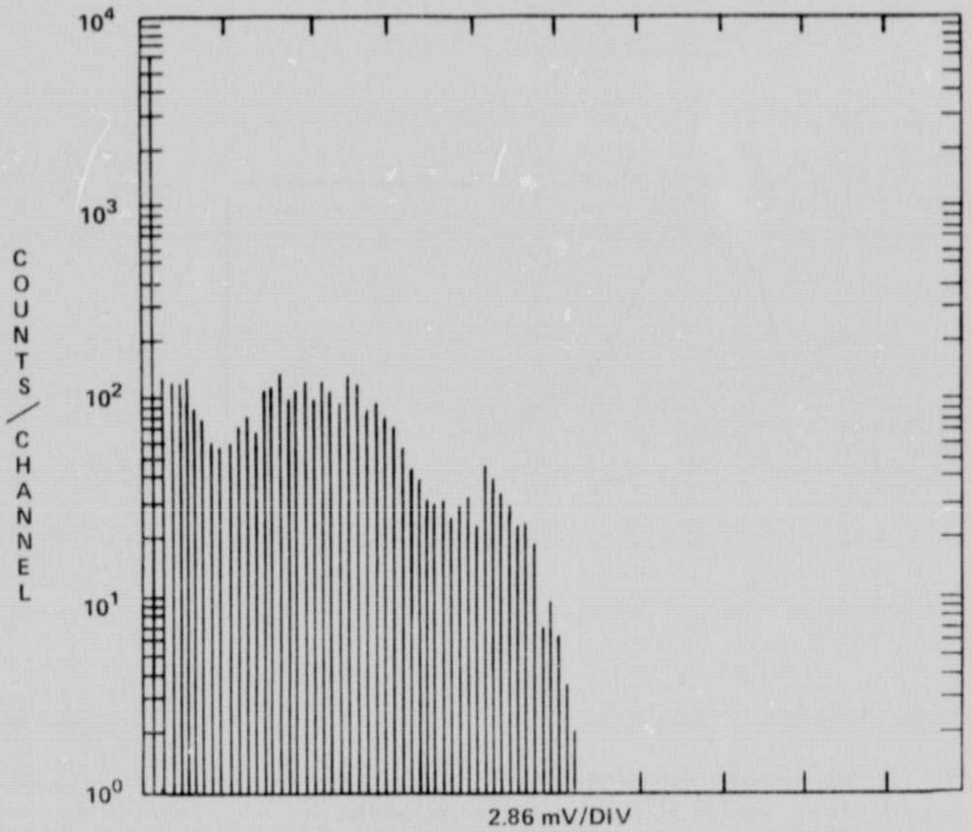

Figure 6. Pulse Height Distribution for Varian 154 A/1.6L Measured with Waveform Digitizer Based System

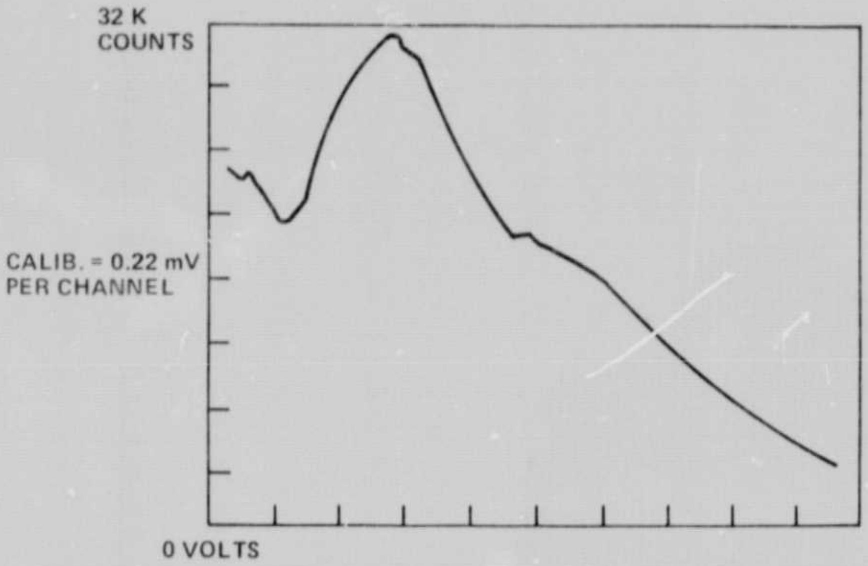

Figure 7. Pulse Height Distribution for Varian 154 A/1.6L Measured with New Measurement System

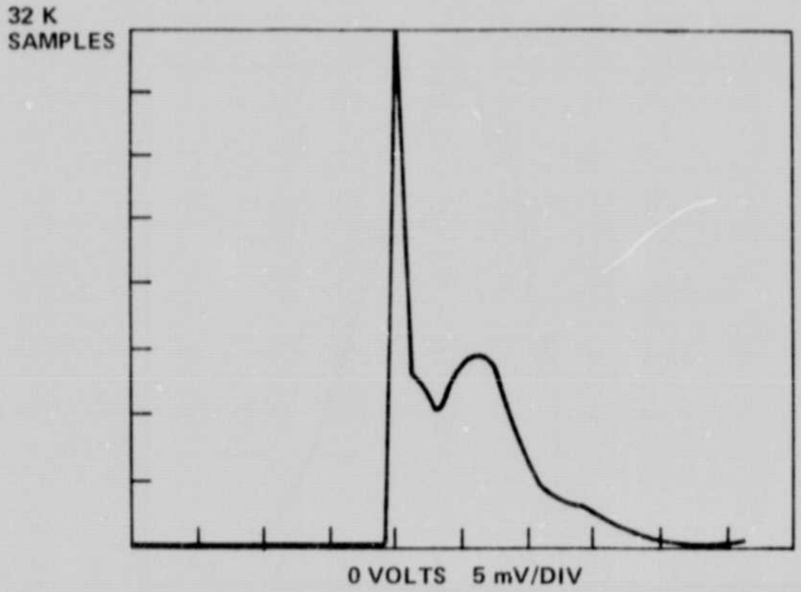

Figure 8. Pulse Height Distribution for Varian 154 A/1.6L Measured with Less System Sensitivity

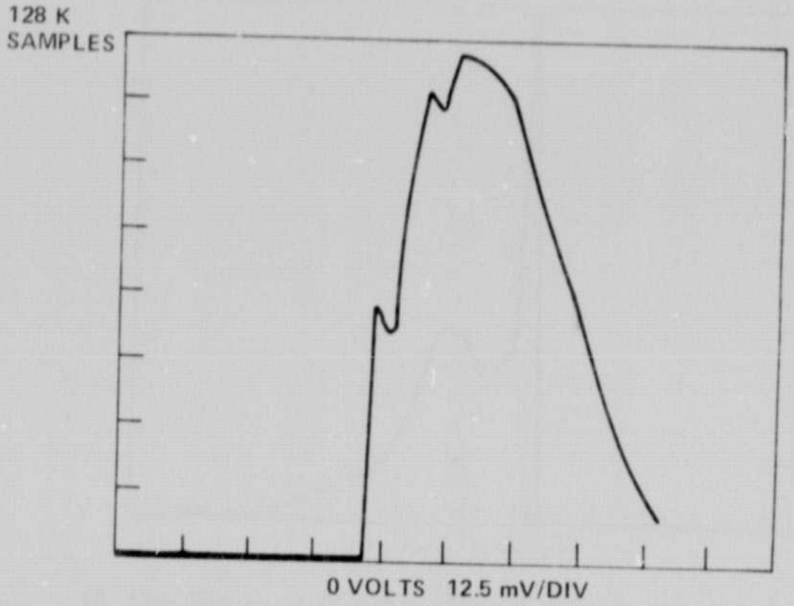

Figure 9. Pulse Height Resolution for Varian 154 A/1.6L Measured at Higher Optical Signal Level

more photoelectrons. The lack of resolution beyond the two-photoelectrons level implies that the GaP(Cs) first dynode of the photomultiplier was not processed for optimum secondary emission multiplication.

The histograms shown in Figures 7 to 9 were taken at a 10-kilohertz sampling rate, and thus only a few minutes were required to compile each one. Since the histogram shown in Figure 6 was taken at a 4-count-per-second rate, the new technique offers a sampling rate increase of 2500 to 1. This speed increase is important, since the laser and electro-optic modulators are subject to slow average power and extinction ratio drifts. Thus the new measurement system is more immune to slow system drifts than the ones used previously. With the combination of high bandwidth, high sensitivity, and good sampling speed, this system should be useful for measuring the pulse height resolution of next generation gigahertz bandwidth photomultipliers.

Acknowledgments

The author wishes to thank Dr. Michael W. Fitzmaurice for discussions and support during this work and H. Edward Rowe for his technical support.

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Figure Captions

Figure 1. System for Measuring Single Photoelectron Voltage of Photomultipliers Using a Sampling Scope

Figure 2. Measured 1.06 μm Pulse Shape

Figure 3. Calculated 0.53 μm Pulse Shape

Figure 4. Histogram of Residual Sampling Noise

Figure 5. Varian 154 A/1.6L Average Pulse Response

Figure 6. Pulse Height Distribution for Varian 154 A/1.6L Measured with Waveform Digitizer Based System

Figure 7. Pulse Height Distribution for Varian 154 A/1.6L Measured with New Measurement System

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Figure 9. Pulse Height Resolution for Varian 154 A/1.6L Measured at Higher Optical Signal Level