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A WIDE-RANGE MULTI-INPUT PULSE HEIGHT RECORDING SYSTEM†

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ABSTRACT

This paper describes a system which can photographically record with one dual-beam oscilloscope the amplitudes of 10 simultaneous photomultiplier pulses over a four-decade dynamic range with an accuracy of ± 1.5% over the entire range. The signal processing time is 2.2 μsec.

The basic circuit is a logarithmic pulse-height-to-time converter with two triggering levels, requiring twelve transistors per input channel. The dynamic range of the device could be easily extended to six decades, and the two-level technique can be applied to digitalized recording systems and pulse height analyzers. The circuit has been built and has been found to meet the above specifications over a temperature range from 0° F to 100° F.

INTRODUCTION

For a cosmic ray experiment[1], it was found necessary to have a data-gathering system which would record the heights of many simultaneous photomultiplier tube pulses whose amplitudes could differ by as much as a factor of 10^4. It was desired that the recording process be finished within 2 μsec after the initiation of the pulses in order to avoid interference from a subsequent high-voltage transient generated elsewhere by the experimental apparatus. The expected event rate is low --- about one per day --- so the data can be recorded in an analogue form on oscilloscope photographs, rather than in a digital form. Yet an accuracy of at least a few percent over the entire range of amplitudes was desired.

There exist at least two other wide-range recording systems[2,3] --- both for cosmic ray experiments --- but they have signal processing times of the order of 100 μseconds. One system requires many oscilloscopes, while the other requires at least 27 transistors per input channel and has only 10% accuracy.

The technique chosen here is a modification of the logarithmic pulse-height-to-time converters used in some analyzers. In those analyzers, the input pulse is admitted through a linear gate and charges a capacitor. The gate is then closed and the capacitor discharges slowly into a level-detector circuit. The decay time constant is usually of the order of milliseconds. In the meantime, a clock oscillator has begun to send pulses to a digital counter, which is started at the instant the capacitor is charged. At the instant the capacitor voltage decays below some preset trigger voltage, the level detector cuts off the clock oscillator. The counter will then register a time which is proportional to the logarithm of the initial voltage to which the capacitor was charged. Some shortcomings of that system are: (1) wide-range linear gates are difficult to build, (2) large pulses require a long time to be processed, and (3) the accuracy begins to suffer when the pulse height gets over 100 times higher than the triggering level. These factors limit the range of pulse heights which can be recorded in a short time with reasonable accuracy.

The system described here overcomes the dynamic range limitation by using several triggering levels which differ by several orders of magnitude. The system uses no linear gates or storage capacitors. Instead, the photomultiplier pulses are applied directly and simultaneously to high- and low-level triggers.

METHOD OF OPERATION

The system makes use of the purely exponential shape of photomultiplier pulses. By varying the anode resistance and capacitance at each photomultiplier, the decay time constant of the pulses is preadjusted to be 432 nsec. When an event occurs, two things happen: a coincidence circuit triggers an oscilloscope sweep, and pulses appear simultaneously on the anodes of each photomultiplier and start to decay. In our particular experiment, we have 20 photomultipliers from which 10 pulses are derived by means of passive mixer circuits. The resulting 10 exponentially-decaying voltages go to 10 two-level pulse-height-to-time converters. (See the system diagram in Fig. 1.)

Each converter consists of two level-detectors (tunnel diode Schmitt triggers) whose sole duty is to emit a short time marker pulse (10 nsec wide) whenever the input voltage falls below a preset level. The upper threshold is 200 mV, and the lower threshold is 2 mV. The input pulse is applied simultaneously to both detectors with one of the three following results:

(1) If the initial amplitude is less than 3 mV, neither detector emits a time marker pulse.

(2) If the initial amplitude is greater than 3 mV but less than 300 mV, the low-level detector will emit a spike at the instant the input voltage decays below 2 mV. The high-level detector will not be triggered.

(3) If the pulse height exceeds 300 mV, both detectors will emit spikes. First the high-level detector is triggered when the input voltage decays through 200 mV. Next the low-level trigger emits a spike when the voltage has decayed through 2 mV. The high- and low-level spikes will always be separated by a fixed interval --- in this case, 2.0 μsec.

Figure 2 illustrates the relevant quantities.

The length of time between the beginning of the event and the occurrence of the spikes will be directly proportional to the natural logarithm of the initial pulse height:

$$(t_h - t_0) = \text{time from start of event to high-level spike}$$
$$= 432 \log_e(E/200) \text{ nsec.}$$
$$(t_\ell - t_0) = \text{time from start of event to low-level spike}$$
$$= 432 \log_e(E/2) \text{ nsec.}$$

where E is the initial amplitude of the pulse in mV. Therefore, the occurrence time of a spike is a measure of the initial pulse height, which can be computed as follows:

$$E = 200 \exp[(t_h - t_0)/432] \text{ mV;}$$
$$E = 2 \exp[(t_\ell - t_0)/432] \text{ mV,}$$

where the time intervals are in nanoseconds.

The high-level spike is positive and the low-level spike is negative. Both of these spikes go the the output of each converter. A dual-beam oscilloscope displays the spikes from all 10 converters, 5 on each beam. The heights of the spikes on the oscilloscope screen are coded so that one can distinguish the spike from one input channel from that of another. A spike from channel 1 is 1/4 cm high, positive or negative; from channel 2, 1/2 cm high, positive or negative; and so forth.

If the oscilloscope trace were exactly 2.0 μsec in length, only one spike from each channel would appear on the trace. (Because if the high-level spike were on the trace, the low-level spike following 2.0 μsec behind the first would be off the trace.) So only five spikes would appear on a trace. However, the trace width to be used in this experiment is 2.2 μsec in order that there be suitable overlapping between upper and lower levels. Thus, in a few cases there may be more than five spikes per trace. Since the spikes are narrow compared to the trace width, they will rarely coincide; and when they do, the information will still be recoverable.

Figure 3 shows a typical oscilloscope display. The polarity of each spike indicates the level triggered, the height of each spike tells which input channel it represents, and the occurrence time of each spike (relative to a dot marking t_0) is a measure of the pulse height in the corresponding input channel. The recording process is completed by photographing the display.

The triggering levels, decay time, and trace width selected give a minimum recordable pulse height of 3 mV and a maximum of 32 V. That is, the dynamic range is more than 4 decades, or 80 db.

CIRCUITRY DETAILS

Each two-level converter is hardly more than three X10 amplifiers in series and two tunnel diode Schmitt triggers. (See Figs. 4 and 5.)

The amplifiers are essentially grounded-base amplifiers with heavy feedback and heavy biasing. The input and output of each stage is negative-going. Each stage is (unnecessarily) linear up to an input voltage of 400 mV, where the amplifiers saturate[4]. The impedence of the converter input is constant (about 50 ohms) up to an input amplitude of 5 V, at which point it drops sharply. This results in an apparent clipping of all pulses at the 5 V level. The clipping does not matter in operation, but it makes calibration more difficult by requiring an isolation emitter-follower for pulses greater than 5 V.

The rather large 120 μf capacitors between stages insure that the exponential pulse will not be quasi-differentiated, so that the circuit response will be purely logarithmic. This makes the amplifiers prone to oscillate at a low frequency unless care is taken in constructing the circuitry and in providing supply voltage filtering. Used to achieve this were ground-plane construction, subminax cable, shielded sections, and filtering with zeners and tantalum capacitors. (See the photograph in Fig. 6.)

The tunnel diodes in their quiescent state are forward biased well into the diode region, at point A in Fig. 8. A negative pulse exceeding 3.0 V sweeps the diode to point B, where it conducts heavily. During the pulse decay the operating point moves toward point C. When the input voltage decays through 2.0 V, the diode snaps off from point C to point D, causing a 300 mV step in the voltage across the diode. (The threshold voltages can be adjusted with the biasing potentiometers, R_3 and R_4.) The rise time of the voltage across the diode is limited by the capacitance to ground at that point; so the circuit construction should minimize stray capacitance across the tunnel diodes.

The differentiators R_1C_1 and R_2C_2 extract a positive spike from the positive-going edge of the tunnel diode pulse. The spike from the high-level trigger goes directly to the output; the low-level spike is first inverted and then sent to the output. The amplitude of both spikes is about 200 mV.

Passive mixer circuits then combine the spikes into two groups of five, and attenuate them according to their channel of origin. The spikes drive two fast linear amplifiers, which in turn drive the inputs of a Fairchild 777 dual beam 100 MHz oscilloscope.

PERFORMANCE AND ACCURACY

Figure 9 shows the actual calibration curve of a typical unit at 68° F. The decay time of the photomultiplier pulse determines the slope of each line; the Schmitt trigger thresholds determine the intercepts. The time constant in this case was in somewhat less than 430 nsec, and the two thresholds were 1.90 mV and 210 mV. Note that no spike could appear before 120 nsec had passed because of the tunnel diode hysteresis. The operating range of amplitudes was 2.80 mV to 35 mV.

The two factors which limit the circuit accuracy in practice are:

(1) Phototube noise pulses which occur during the 2 μsec processing time or a few microseconds before the event.

(2) The precision with which one can measure the occurrence time of a spike from a photograph.

The error due to phototube noise will be small whenever the signal is higher than the average noise pulse, and in our application the signal levels are so high that this error is completely negligible[5].

The relative error in the pulse height E due to the errors $\Delta(t_h - t_0)$ in measurement of the time interval $(t_h - t_0)$ is approximately $[\Delta(t_h - t_0)]/(432 \text{ nsec})$.

The same relation applies to the lower level. The percentage error is independent of pulse height, and it depends only on the size of the time error as compared to the decay constant of the pulse. A measure of the reading error $\Delta(t_h - t_0)$ is the halfwidth at half-maximum of the output pulses, i.e., 5 nsec. The corresponding percentage error is $\pm$ 1.2%.

Temperature variation and internal circuit noise contribute less error than the reading error. The low-level pulse has some time jitter due to amplifier noise. This jitter is about $\pm$ 2 nsec ($\pm$ 0.5%). The high-level pulse has no measureable jitter. The circuit has been tested from 0° F to 100° F. The average temperature variation of a typical unit was + 0.05% per deg F for the low level and - 0.01% per deg F for the high level. The largest temperature error was 0.09% per deg F. Since we will control the circuit temperature to ± 5° F, our error due to temperature variations will be less than ± 0.5%. The rms value of all these errors (thermal, noise jitter, and measurement errors) is 1.4%.

In summary, the circuit can handle input amplitudes from 3 mV to 35 V, with the output representing the input to an accuracy of about ± 1.5% over the whole range of input amplitudes.

POSSIBLE IMPROVEMENTS

A new design incorporating the same principles should use a more simple amplifier, one which is not as linear as the one described here[4]. Also, each tunnel diode should drive an avalanche transistor directly. This would eliminate the necessity for the linear amplifiers which drive the oscilloscope, and it would provide narrower spikes.

Each level could cover three decades instead of two, or additional levels with different coding could be used to increase the dynamic range to six or seven decades. Multichannel analyzers could use a linear decay with several (non-zero) triggering levels to extend their range and accuracy. When inexpensive 100 MHz scalers become available the output could be easily digitalized.

Because it selects amplitude ranges in a natural way, the multilevel technique is applicable to a variety of experiments.

ACKNOWLEDGEMENT

I want to thank Mr. Wolfgang Schmidt for clearly outlining the shortcomings of conventional analyzers to me, and for suggesting that tunnel diodes be tried as Schmitt triggers.

FOOTNOTES AND REFERENCES

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1. The experiment consists in part of a total absorption spectrometer designed to measure the energies of the primary particles in individual ultra high energy interactions. Two problems often arise in this type of experiment. One problem is the dynamic range, which must be large because:

   (a) the experiment must accept a wide range of primary energies, and

   (b) for a given primary energy, there can be large fluctuations in the development of the electromagnetic cascade in the spectrometer.

   A second problem is the large number of detectors --- from 10 to 20 --- whose outputs must be individually recorded. The experiment is part of a cosmic ray laboratory now being built at an altitude of 12,000 ft near Climax, Colorado, by a group from Louisiana State University headed by Professor R. W. Huggett.

2. N. L. Grigorov et.al., Pribory i Tekhnika Eksperimenta, No. 1, pp. 100-106, Jan. Feb., 1966. Trans. by Instrument Society of America under title Instruments and Experimental Techniques in Sept. 1966, p. 102.

3. P. V. Ramana Murthy, B. V. Sreekantan, A. Subramanian, and S. D. Verma, Nucl. Inst. & Methods 23, 245 (1963).

4. Saturation of the amplifier does not matter, since the amplifiers only chop off the top of the pulse at 4 V, whereas the triggers operate at 2 V. That is, the voltage at the low-level trigger decays through 2.0 V only a few nanoseconds after the instant that the input has decayed through 2 mV --- regardless of saturation at 4 V --- and this instant is all that the circuit is concerned with. For this reason, the amplifiers do not have to be linear over four decades. In fact, they do not have to be linear at all.
5. Consider the following example of the worst case: We had at one time an uncooled 5 in photomultiplier (RCA 8055) 2 ft away from the thin edge of a 1 inch thick plastic scintillator. With the photomultiplier voltage at 1800 v, the average pulse height due to minimum-ionizing muons passing through an area which was 2-3 ft within the scintillator was about 65 mV. This is certainly a low-signal application, with at most about 100 photons hitting the photocathode on the average. Yet the frequency of noise pulses greater than 32 mV was about 1850 pulses per sec. That is, the probability of a noise pulse greater than half the average signal pulse height occurring in any particular 2 μsec interval is less than 1/2%, even in this worst of cases. In our application the light intensities will be from 10^2 to 10^6 times as high; so noise is not a problem.

CAPTIONS FOR FIGURES

Fig. 1. Block diagram of pulse height recording system.

Fig. 2. Relevant quantities in pulse-height-to-time conversion. Upper graph shows typical input to a converter, superimposed on the two triggering levels of the converter. E is initial amplitude of pulse. Lower graph shows output of the converter. t_0 is the starting time of event; t_h and t_ℓ are the times that the pulse decays through the upper and lower levels, respectively.

Fig. 3. Typical oscilloscope display of system output. Reference dot marks start of event. Height of each spike identifies channel of origin; polarity indicates whether high- or low-level; occurrence time indicates amplitude of corresponding input pulse.

Fig. 4. Block diagram of one of the two-level height-to-time converters.

Fig. 5. Circuit diagram of the two-level height-to-time converter. The 120 μf, 15 μf, 6.8 μf, and 1.5 μf capacitors are tantalum electrolytics. C_3, C_4, C_5 are Erie .001 μf feedthrough capacitors. The .01 μf, .001 μf, and 390 pf capacitors are ceramic. All resistors are 1/4 watt unless otherwise indicated. The 1% resistors are IRC CEM T-0 metal film resistors. Q_1, Q_3, Q_4,..., Q_8 are 2N3905's; Q_2 is a 2N3250; Q_9, Q_{10}, Q_{11}, Q_{12} are 2N708's; D_1, D_2, D_3, D_4 are 1N47394 zener diodes; D_5 and D_6 are 1N3712 tunnel diodes; D_7 and D_8 are 1N914

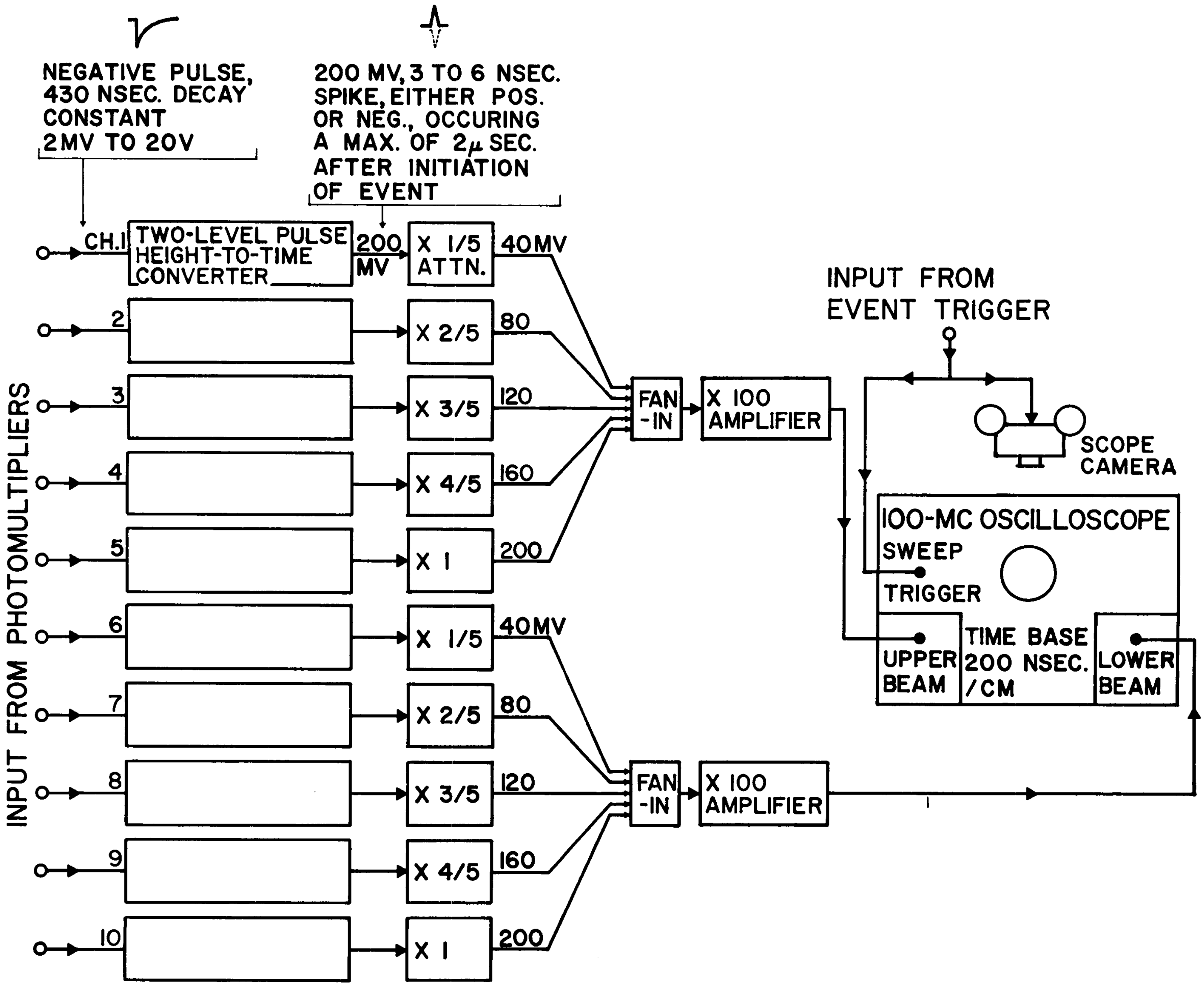
diodes; T_1 is an inverter transformer: 10 bifilar turns on a Ferroxcube 1041T060/3E2A core. (Core is not critical.)

Fig. 6. Two-level converter module, and bin containing ten modules. The high- and low-level triggers are at the lower and upper left, respectively. The three amplifier stages are at the upper right-hand side of the module. Note ground plane, printed circuit construction, and interstage shielding.

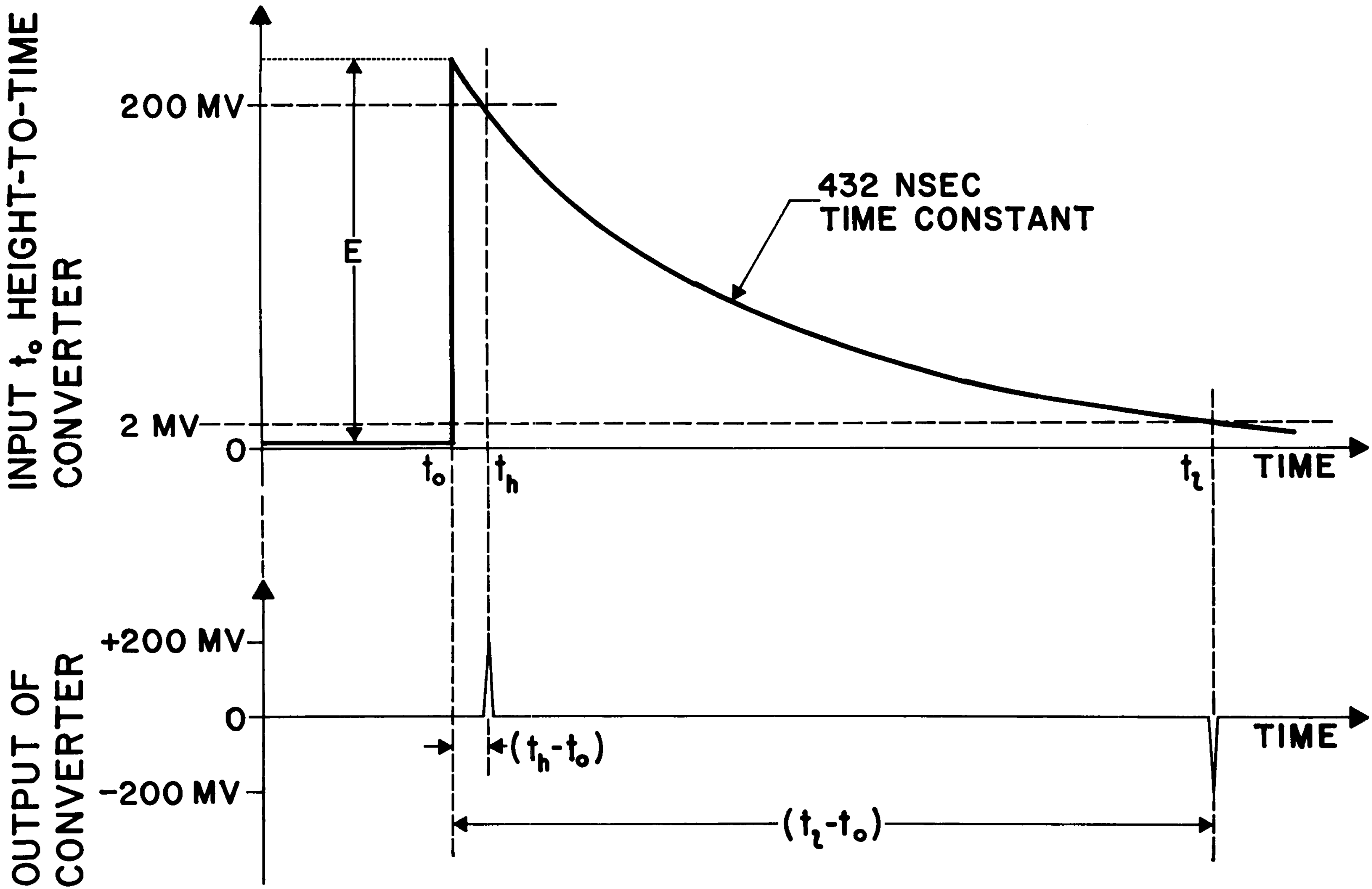
Fig. 7. Output spike from converter. 10 nsec/cm.

Fig. 8. Voltage-versus-current characteristic of tunnel diode level detector, showing sequence of operation. Point A is quiescent state.

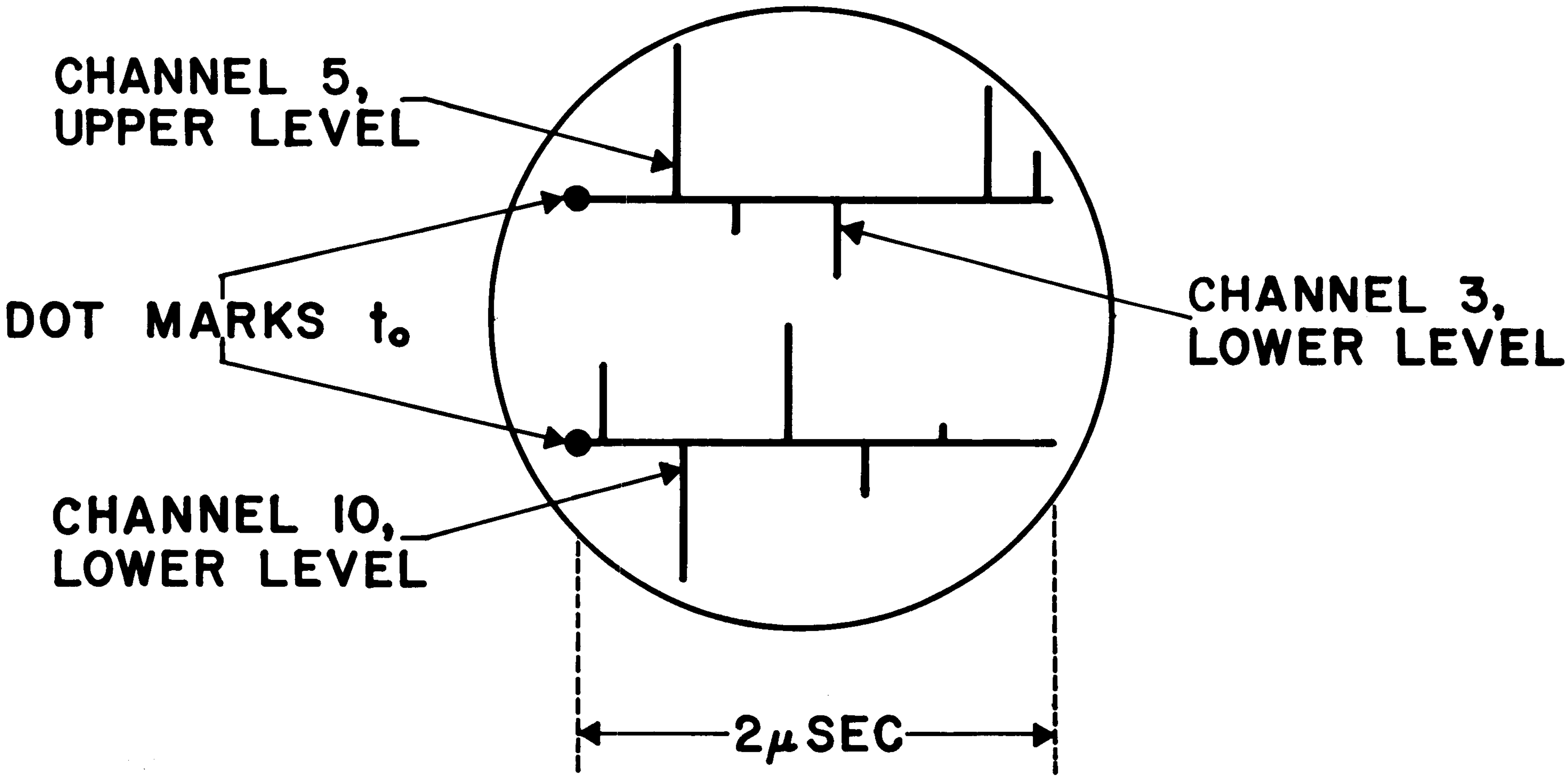
Fig. 9. Actual calibration curve of a typical converter module at 68° F. Curves at 100° F and 0° F do not differ enough to show on graph.

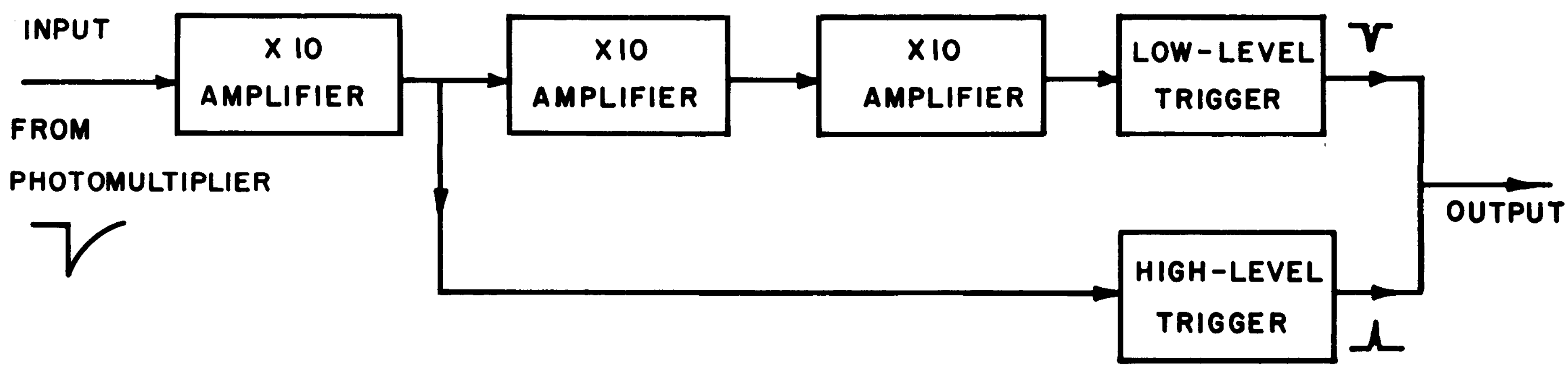

NEGATIVE PULSE, 430 NSEC. DECAY CONSTANT 2MV TO 20V
200 MV, 3 TO 6 NSEC. SPIKE, EITHER POS. OR NEG., OCCURING A MAX. OF 2μ SEC. AFTER INITIATION OF EVENT
CH.1
TWO-LEVEL PULSE HEIGHT-TO-TIME CONVERTER
200 MV
X 1/5 ATTN.
40MV
2
3
4
5
6
7
8
9
10
X 2/5
X 3/5
X 4/5
X 1
X 1/5
80
120
160
200
40MV
FAN -IN
X 100 AMPLIFIER
INPUT FROM EVENT TRIGGER
SCOPE CAMERA
100-MC OSCILLOSCOPE
SWEEP
TRIGGER
UPPER BEAM
TIME BASE 200 NSEC. /CM
LOWER BEAM
INPUT FROM PHOTOMULTIPLIERS

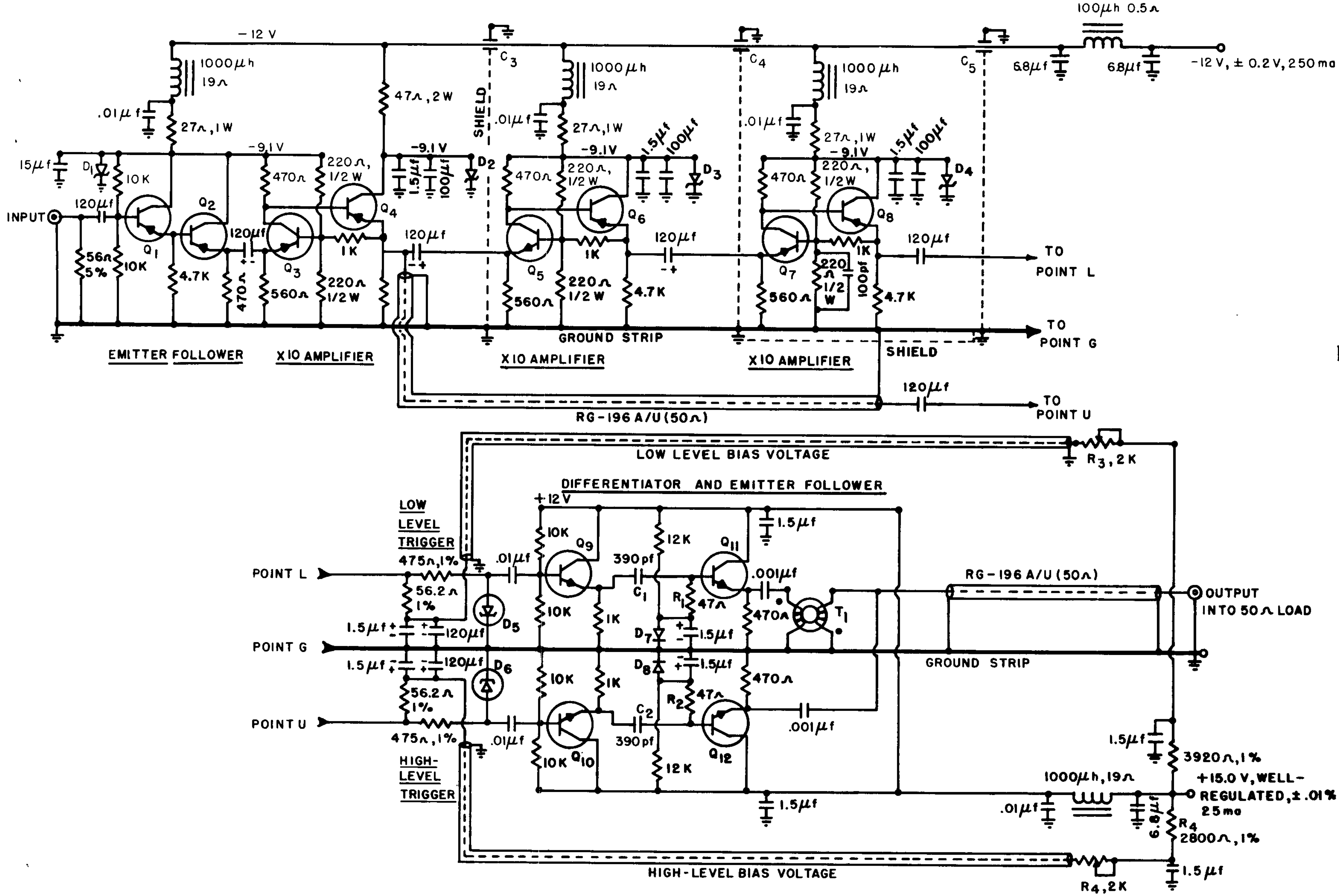
1

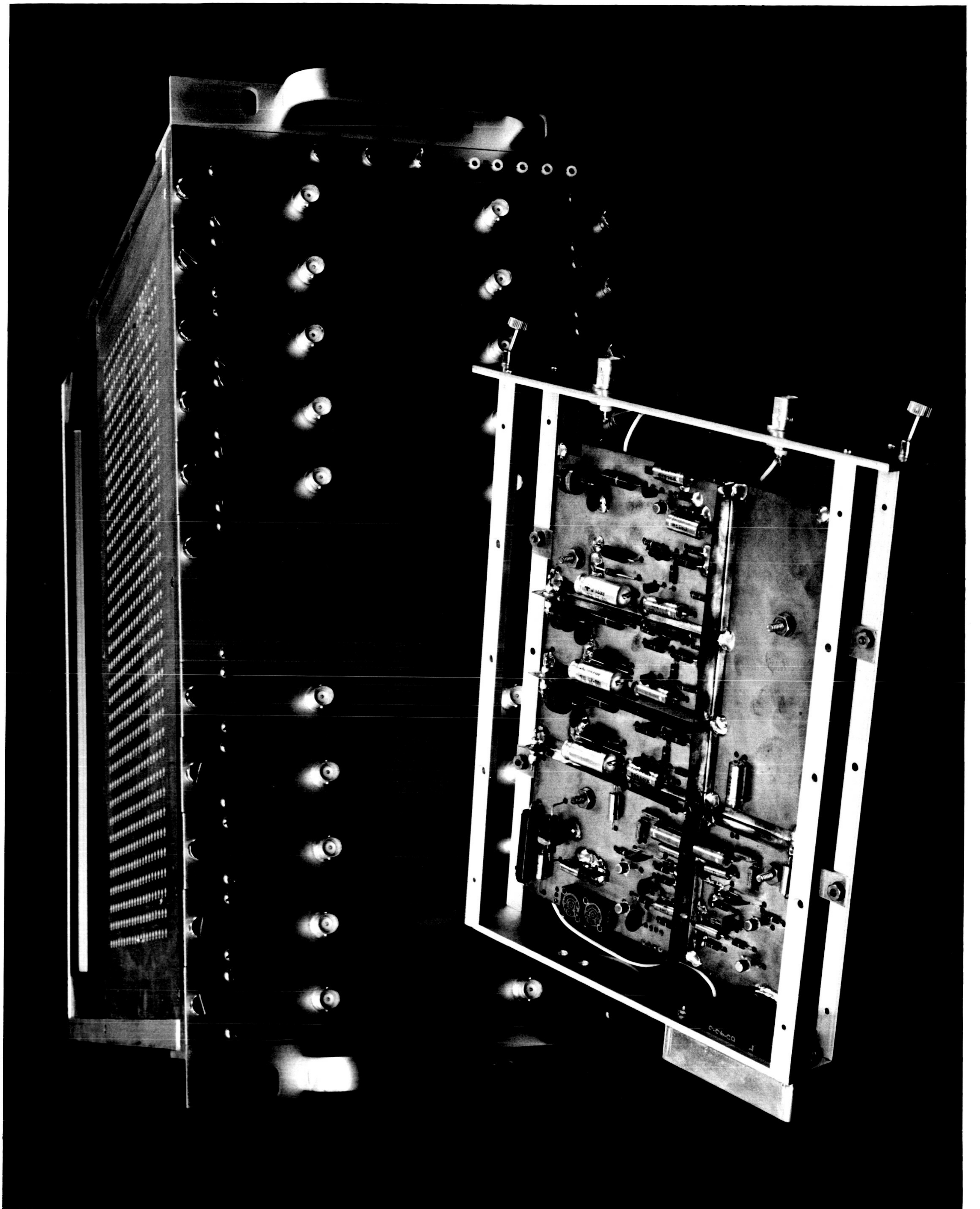


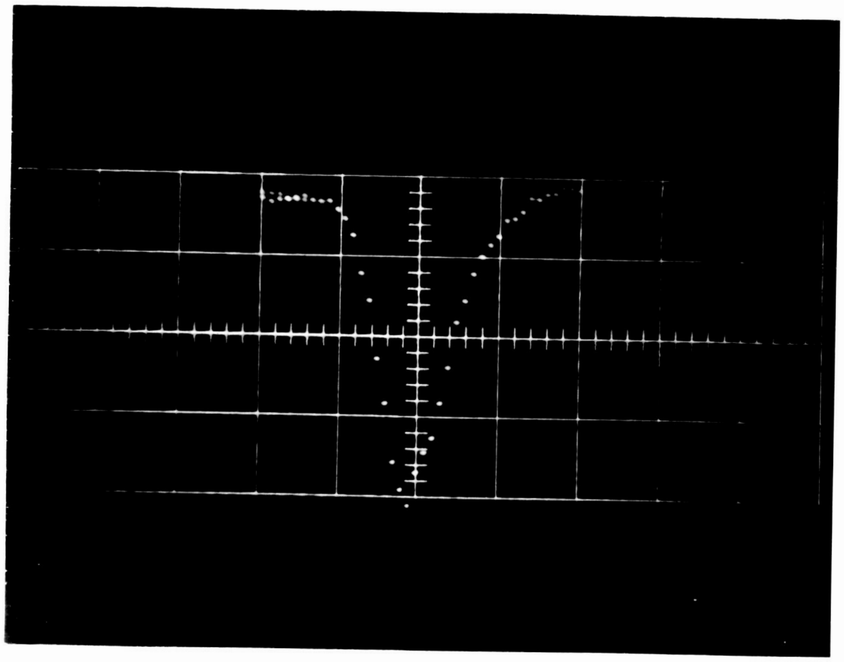
INPUT to HEIGHT-TO-TIME CONVERTER
200 MV
2 MV
0
E
432 NSEC
TIME CONSTANT
t_o
t_h
t_l
TIME
OUTPUT OF CONVERTER
+200 MV
0
-200 MV
(t_h-t_o)
(t_l-t_o)
TIME


CHANNEL 5,
UPPER LEVEL
DOT MARKS t_0
CHANNEL 10,
LOWER LEVEL
CHANNEL 3,
LOWER LEVEL
2μSEC

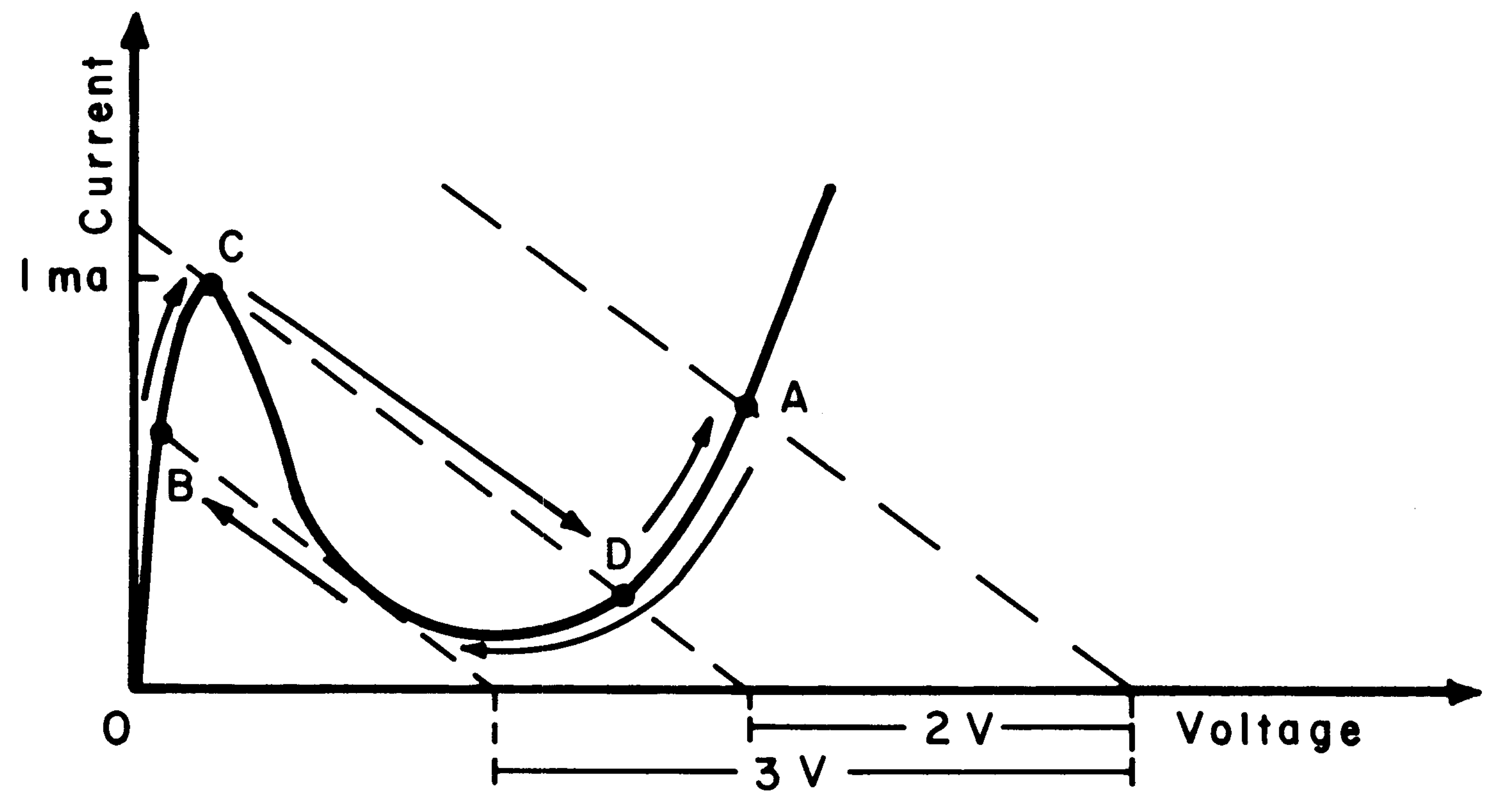

INPUT
FROM
PHOTOMULTIPLIER
X 10
AMPLIFIER
X10
AMPLIFIER
X10
AMPLIFIER
LOW-LEVEL
TRIGGER
HIGH-LEVEL
TRIGGER
OUTPUT


-12 V
100µh 0.5Ω
6.8µf
-12 V, ± 0.2 V, 250 ma
1000µh
19Ω
.01µf
27Ω, 1W
47Ω, 2W
-9.1V
15µf
INPUT
120µf
10K
56Ω 5%
4.7K
470Ω
560Ω
220Ω, 1/2 W
1K
1.5µf
100µf
SHIELD
C3
C4
C5
EMITTER FOLLOWER
X10 AMPLIFIER
GROUND STRIP
TO POINT L
TO POINT G
TO POINT U
RG-196 A/U (50Ω)
LOW LEVEL BIAS VOLTAGE
R3, 2K
DIFFERENTIATOR AND EMITTER FOLLOWER
+12 V
LOW LEVEL TRIGGER
HIGH-LEVEL TRIGGER
POINT L
POINT G
POINT U
475Ω, 1%
56.2Ω 1%
.01µf
390 pf
12K
47Ω
.001µf
OUTPUT INTO 50Ω LOAD
3920Ω, 1%
+15.0 V, WELL-REGULATED, ±.01% 25 ma
1000µh, 19Ω
R4 2800Ω, 1%
R4, 2K
HIGH-LEVEL BIAS VOLTAGE





7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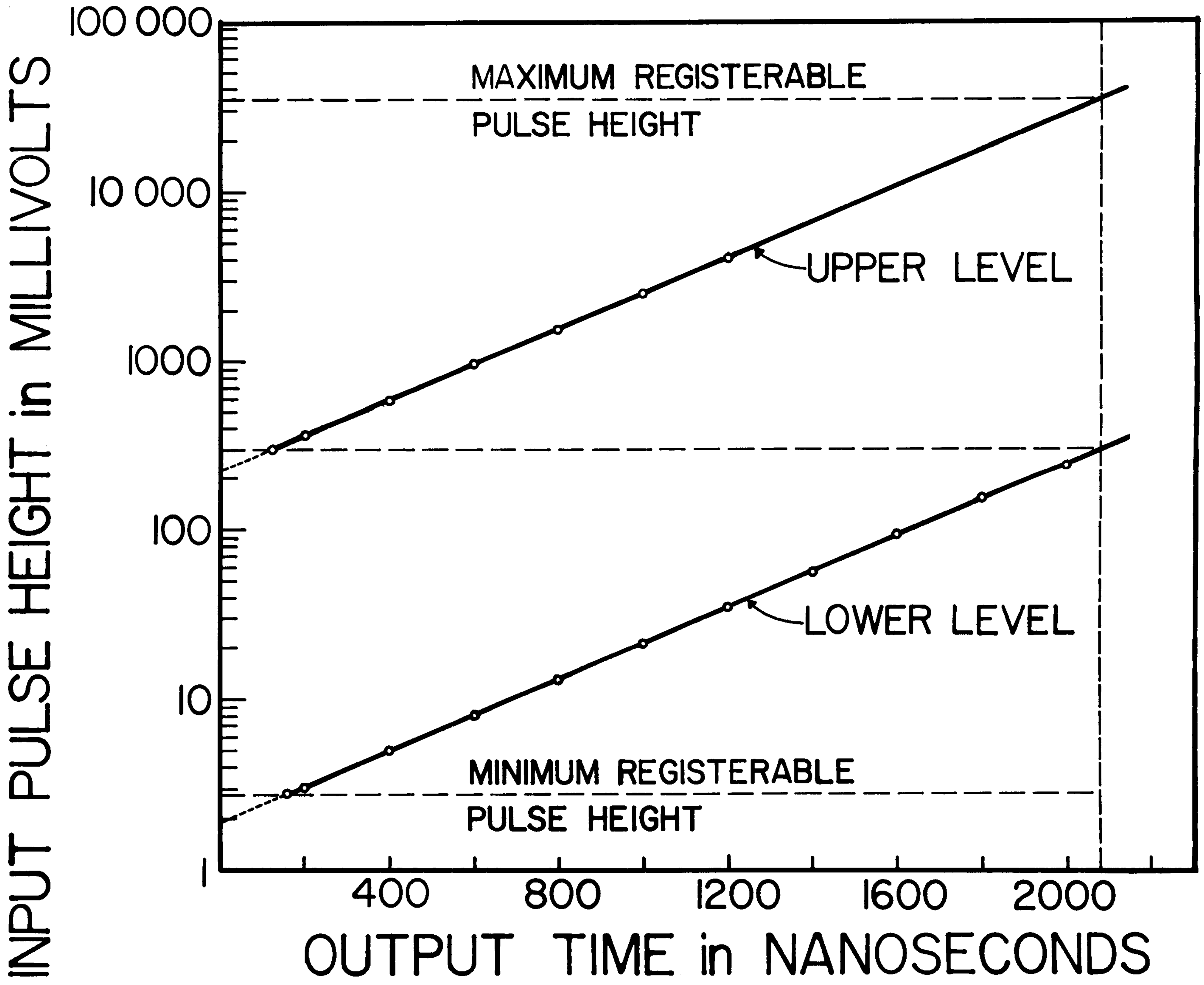
I ma
C
A
B
D
O
2 V
3 V
Voltage


INPUT PULSE HEIGHT in MILLIVOLTS
100 000
10 000
1000
100
10
1
400
800
1200
1600
2000
OUTPUT TIME in NANOSECONDS
MAXIMUM REGISTERABLE PULSE HEIGHT
UPPER LEVEL
LOWER LEVEL
MINIMUM REGISTERABLE PULSE HEIGHT