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FREQUENCY HETERODYNING IN PHOTOMULTIPLIER TUBES

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ARO, Inc.

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NOTICES

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FOREWORD

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This technical report has been reviewed and is approved.

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ABSTRACT

Photomultiplier tubes with a suitable electrode structure were investigated for use in a superheterodyne-type signal receiver for the Doppler shift laser velocimeter (LV). An oscillator signal impressed upon specially constructed electrodes within the photomultiplier tube produced a signal at a frequency which was the difference between the oscillator and the LV signal frequencies. The high gain of the photomultiplier tube then amplified the difference frequency signal to a usable level. Two different tubes were investigated and found to be useful as heterodyne photomultiplier tube amplifiers. The circuit design, experimental results, and applications are discussed.

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Illustrations

NOMENCLATURE

IF	Intermediate frequency
LED	Light emitting diode
LV	Laser velocimeter (Doppler shift principle)
PM	Photomultiplier tube

SECTION I
INTRODUCTION

Three significant problems, among many others, associated with the development of a practical Doppler shift laser velocimeter (LV) are (1) the poor signal-to-noise ratios often encountered, (2) the large frequency range (0 through hundreds of megahertz) of operation demanded of a versatile LV, and (3) the high gain often required of the photodetector component of the LV.

Readily available photomultiplier (PM) tube photodetectors can provide wideband (0 to 200 MHz) high gain (10^4 amp/watt) amplification of a photodetected LV signal which solves problems 2 and 3 for the lower frequency range. Because of its upper cutoff frequency at several hundred megahertz, the conventional PM tube must be replaced by one with microwave response capabilities for use above this cutoff frequency. A superheterodyne-type LV signal receiver employing a PM tube can be used to recover a constant wave LV signal (as opposed to a frequency burst signal) from significant noise levels and this is one approach for solution of problem 1. A manually tuned superheterodyne receiver is shown in Fig. 1a. A somewhat more complex but more desirable automatic frequency tracking superheterodyne receiver is shown in Fig. 1b. These receivers can function in spite of significant noise levels because of the narrow bandpass characteristics of the intermediate frequency (IF) amplifier. However, the useful frequency range of the receiver would ultimately be limited by the frequency response characteristics of the PM tube.

Oscillator signals can be injected into certain PM tubes and heterodyned with the photodetected LV signal to produce a signal with a frequency that is the difference of the LV and oscillator frequencies. This heterodyning process can be produced in the region of the PM tube photocathode so that the full gain of the PM tube is available to amplify the difference signal. From Fig. 1 it can be shown that a heterodyne PM tube could be used in place of the conventional PM tube and separate frequency mixer. With the heterodyne PM tube the possibility exists of exploiting the heterodyning process to maintain the difference frequency signal within the frequency response limitations of the PM tube and thereby increase the useful frequency range beyond the several hundred megahertz frequency response limitation of the otherwise conventional PM tube. A single PM tube opertaing beyond this frequency range is not commercially available at this time. However, experiments were performed with two PM tubes in which the heterodyning process was accomplished over the frequency range from 1 kHz to 100 MHz. One of the tubes had an upper cutoff frequency of approximately 30 MHz and that of the second tube was approximately 100 MHz.

This report contains (1) a fundamental discussion of the PM tube heterodyne process and (2) a detailed discussion of the results of the heterodyning experiments performed with the two PM tubes.

SECTION II
FUNDAMENTAL CONSIDERATIONS

2.1 OPTICAL FREQUENCY HETERODYNING

The conventional reference beam LV produces two beams of laser radiation: (1) a reference beam and (2) a scattered beam. The reference beam originates from a laser, whereas the scattered beam results from a scattering interaction with impurities in the flowing fluid. Because of the scattering interaction, the scattered radiation experiences a Doppler shift in optical frequency. The LV optical system is designed so that the wave vectors of the two beams are aligned to precise coincidence at the surface of a photodetector.

The photodetector produces an output current which is a linear function of the incident radiation intensity. The reference beam can be represented by

$$E_r \cos(\omega_r t + \phi_r) \tag{1}$$

and the scattered beam by

$$E_s \cos(\omega_s t + \phi_s) \tag{2}$$

where E_r and E_s are the peak electric fields of the reference and scatter beams, respectively (both with the same polarization), ω_r and ω_s are the radian frequencies, and ϕ_r and ϕ_s are phase constants. The incident radiation intensity is proportional to the square of the total incident electric field. Therefore the photoemitted electron current is proportional to

$$\begin{aligned} [E_r \cos(\omega_r t + \phi_r) + E_s \cos(\omega_s t + \phi_s)]^2 &= \frac{E_r^2 + E_s^2}{2} + E_r^2 \cos 2(\omega_r t + \phi_r) \\ &+ E_s^2 \cos 2(\omega_s t + \phi_s) + E_r E_s \cos[(\omega_r + \omega_s) t + \phi_r + \phi_s] \\ &+ E_r E_s \cos[(\omega_r - \omega_s) t + \phi_r - \phi_s] \end{aligned} \tag{3}$$

Equation 3 is a mathematical description of the optical frequency heterodyning process which occurs at the photocathode of the photodetector. Equation 3 predicts a direct current signal, a current varying at twice the frequency of the reference radiation, one varying at twice the frequency of the scattered radiation, one varying at the sum of the two beam frequencies, and a current varying at the difference of the two beam frequencies. However, the photodetector will respond only to the direct current and difference frequency signals since the others vary at optical frequencies. The frequency of the difference frequency signal is directly proportional to the velocity of the scattering particles in the fluid flow and is the signal of interest.

A light source device utilizing a light emitting diode (LED) was developed[1] to simulate the LV system signal. The PM tube response to either the LV system or the LED device is shown in Fig. 2a. The direct current and sinusoidally varying components of the signal are evident. Figures 2b and c will be explained in the following paragraphs.

2.2 PHOTOMULTIPLIER TUBE FREQUENCY HETERODYNING

The two PM tubes used in this study possessed control grid structures in proximity to the photocathode so that an electric field established between these two electrodes could amplitude modulate the photoemitted electron current. A static potential, $-v_1$ (see Fig. 2b), is impressed upon the control grid such that the resultant electric field repels practically all the photoemitted electrons back to the photocathode. A sinusoidal modulating signal (see Fig. 2b) is next applied between the control grid and photocathode so that each positive excursion of this waveform permits one pulse of the available photoemitted electron current to pass from the photocathode through the control grid structure and on to the PM tube dynode assembly. The voltage v_c (Fig. 2) is the approximate value required for switching the photoemitted current. Actual PM tube control grid characteristics exhibit a more gradual turn on and cutoff characteristic than that shown in Fig. 2. The available electron current varies at the frequency f_1, whereas the control grid modulating frequency is f_2. This heterodyning process produces current pulses with the repetition frequency $f_2 - f_1$. A low pass filter placed at the output of the PM tube integrates the current pulses and produces the voltage waveform shown in Fig. 2c.

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[1]F. L. Crosswy and H. T. Kalb. "Intensity Modulated Light Source Usable to 100 MHz." AEDC-TR-70-34 (AD702094), March 1970.

The above-described heterodyning process was applied to both of the PM tubes used in this study.

SECTION III APPARATUS AND PROCEDURE

3.1 PHOTOMULTIPLIER TUBES

The PM1 PM tube is shown in Fig. 3. The photoemitted electron current is produced at the PM tube photocathode by the LV system laser light. The static electric field and the sinusoidal modulating signal are produced at the photocathode by applying these signals to the control grid structure shown in Fig. 3. The transconductance curve for this PM tube is shown in Fig. 4 along with the control grid input and PM output current waveforms. As shown in Fig. 4 the control grid static bias voltage, $-v_1$, was held at -1 v. The electrical connections for the PM1 are shown in Fig. 5. The oscillator signal was introduced into the PM tube by means of the modulator transformer shown in Fig. 5.

The PM2 PM tube is shown in Fig. 6. The photoemitted electron current is produced at the PM tube photocathode by the LV system laser light. The static electric field and the sinusoidal modulating signal are produced at the photocathode by applying these signals to the control grid as shown in Fig. 6. The variation of the control grid to photocathode electric field distribution and photoelectron trajectories as a function of control grid to photocathode potential difference is shown in Fig. 7. Figure 7 shows that amplitude modulation of the control grid to photocathode potential difference produces a corresponding modulation of the photoelectron stream. The transconductance curve for this PM tube is shown in Fig. 7d along with the control grid input and output current waveforms. As shown in Fig. 7d, the control grid static bias voltage was held at -20 v. The electrical connections for the PM2 are shown in Fig. 8. The oscillator signal was introduced into the PM tube by means of the modulator transformer shown in Fig. 8.

The assembly containing the PM tube, electrode bias device and modulation transformer is shown in Fig. 9. The PM1 PM tube is shown in Fig. 9 and the assembly for the PM2 was similar.

3.2 INSTRUMENTATION

The instrumentation for investigating the frequency heterodyning characteristics of the two PM tubes is shown in Fig. 10. The light source device, utilizing a solid-state light emitting diode (LED), was used to simulate LV system signals up to 100 MHz.[2] The oscilloscope was used to observe low frequency, large amplitude PM tube signals whereas the spectrum analyzer was used to observe low level high frequency signals. A photograph of the instrumentation and experimental arrangement is shown in Fig. 11.

SECTION IV
RESULTS AND DISCUSSION

4.1 PM1 PHOTOMULTIPLIER TUBE

The rated anode rise time for the PM1 PM tube is $16(10^{-9})$ sec. This indicates a frequency domain response flat to about 25 MHz. It had previously been determined that the 3-db cutoff frequency of the light source (Figs. 10 and 11) was about 15 MHz.[3] The highest useful frequency of the light source was found to be 100 MHz. The PM1 response to the 100 MHz sinusoidally intensity modulated light source signal is shown in Fig. 12. Light signals much above 100 MHz could not be distinguished from signals caused by stray pickup.

Figure 13 shows the current probe (Figs. 10 and 11) presentation for an LED static bias current of 26 ma and a 35-MHz sinusoidal driving current of 56 ma peak to peak. A triple exposure of the film was employed to record the two waveforms and the zero reference. The PM1 response to these driving conditions is shown in Fig. 14. The noise accompanying the 35-MHz signal is PM tube generated white noise caused by the static bias light level. Figures 12, 13, and 14 illustrate the responses obtained from the PM1 for light source excitations alone. The frequency heterodyning characteristics were next determined.

Figure 15 shows the PM1 time domain response to a 10-MHz light source signal and a 9.75-MHz modulating signal. This waveform is that predicted by the graphical analysis in Fig. 2. The envelope amplitude modulation at the 250-kHz difference frequency is evident. The

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[2]Ibid.

[3]Ibid.

frequency domain spectrum analyzer was next used to display the data for the range of frequencies beyond the flat response bandwidth of the time domain instrumentation.

Figure 16 shows the spectrum analyzer display for an 80-MHz light source signal, a 50 MHz modulation signal and a 30-MHz difference frequency signal. It is significant to note that the amplitude of the 30-MHz difference signal is a factor of five larger than that of the original 80-MHz signal. This can be explained by the fact that the 80-MHz signal is well beyond the 25-MHz cutoff frequency of the PM tube and is attenuated, whereas the 30-MHz signal is not.

Satisfactory heterodyning action (difference frequency signal ≥ -45 dbm) could be observed for light source frequencies up to 100 MHz and modulator frequencies up to 60 MHz. The 100-MHz limit was caused primarily by light source inadequacy above this frequency. The PM1 modulator grid structure was not designed for high frequency operation which explains the 60-MHz modulator limitation. However, the data of Fig. 16 might provide encouragement for development of high frequency response modulator grid structure PM tubes.

4.2 PM2 TVP PHOTOMULTIPLIER TUBE

The PM2 PM tube grid structure was not designed for frequency heterodyning. Figure 7d also shows that the tube transconductance is relatively small and that large amplitude modulator signals would be required for frequency heterodyning. However, useful difference frequency signals were obtained.

Figure 17 shows the spectrum analyzer display of the PM2 output for a light source signal at 110 MHz, a modulator signal at 60 MHz, and a difference frequency signal at 50 MHz. The spurious signals were introduced by the oscillator and power amplifier which were driven at peak output levels and, therefore, into nonlinearity to produce heterodyning action. An oscillator and power amplifier with higher voltage and power ratings could probably have been used without introduction of spurious signals. Usable heterodyne signals (≥ -50 dbm) were obtained for light source signals up to 110 MHz and modulator signals up to 60 MHz.

SECTION V
SUMMARY OF RESULTS AND CONCLUSIONS

Two commercially available PM tubes, the PM1 and the PM2, were obtained for frequency heterodyne experiments. Both tubes were found to be suitable for use in a superheterodyne circuit for receiving constant wave LV system signals. The PM1 was more convenient to use because of the lower modulator drive levels required for frequency heterodyning. Both tubes produced usable ($\geq$-50 dbm) difference frequency signals for light source signals as high as 100 MHz and modulator signals as high as 60 MHz. The 100-MHz limit was dictated by the upper useful frequency range of the light source; the PM tubes could probably have been used at higher frequencies. The 60-MHz modulator limit was caused by the lead-in wires to the modulator grid structure and the grid structure itself since these were not designed and constructed for high frequency operation. The use of transmission line lead-in wires and a control grid structure designed for proper termination of the transmission line could significantly increase the useful frequency range of the modulator grid structure.

The data for the PM1 PM tube demonstrated that the useful frequency response range could be increased by frequency heterodyning. An otherwise conventional PM tube provided with a high frequency heterodyne control grid structure could represent an operational simplification for LV systems operating with constant wave signals since (1) it could be used in a conventional manner without heterodyning, (2) exploiting the heterodyne capability, the tube could be incorporated directly into a superheterodyne circuit, and (3) the increased useful frequency range could eliminate the need for microwave response PM tubes at least for the lower end of the microwave spectrum.

Section 2.1 provided the physical description of the optical heterodyne process for a reference beam LV. The heterodyne PM tubes were initially investigated for use with these types of LV systems. However, these tubes and the superheterodyne-type signal conditioning instruments are directly usable with the recently developed dual-scatter-type LV systems. The dual-scatter LV system optically heterodynes two or more scatter beams to extract the Doppler information as compared to the reference-beam-type LV system which optically heterodynes a scatter beam and a reference beam.

APPENDIX
ILLUSTRATIONS

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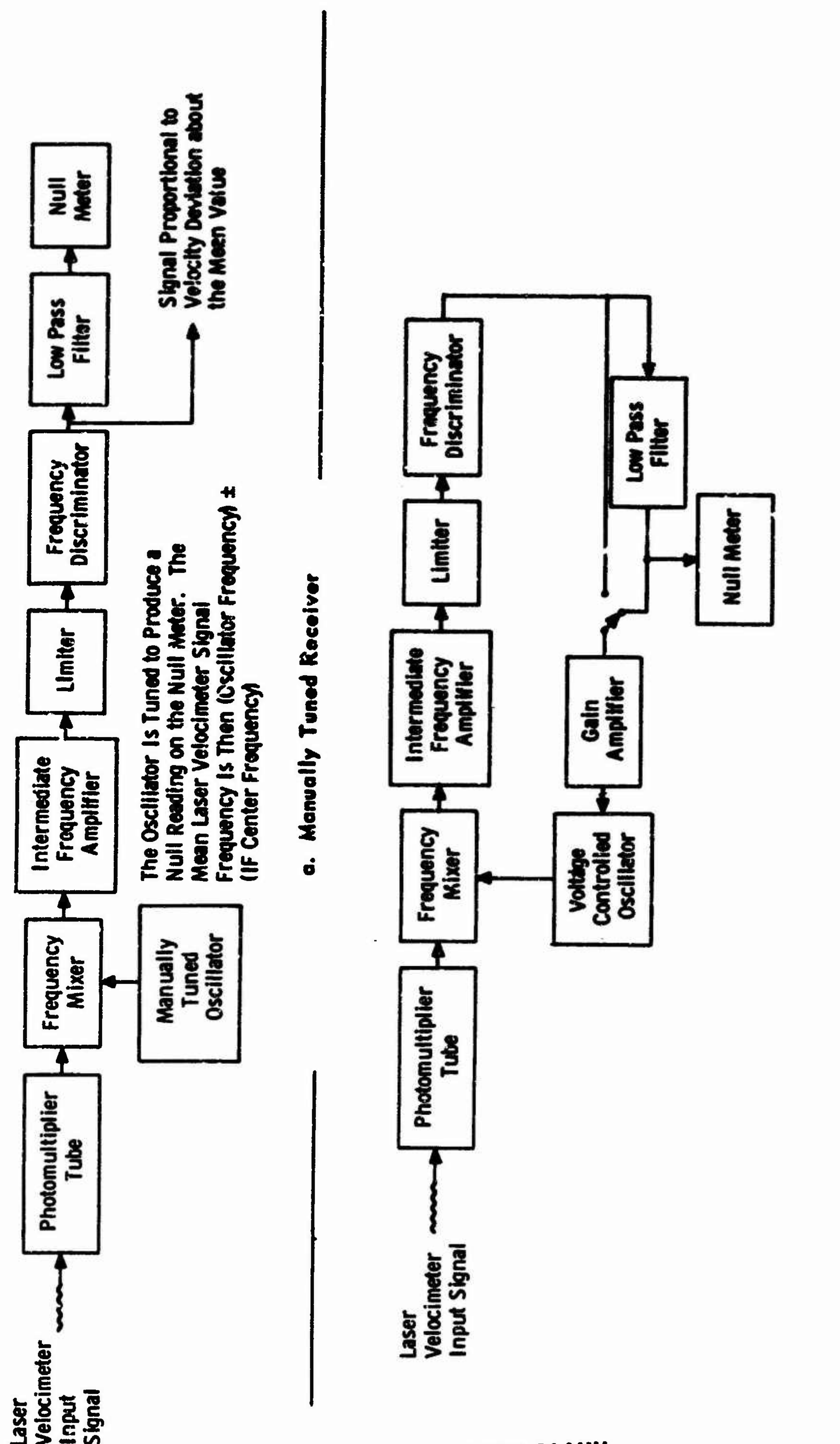

b. Automatic Frequency Tracking Receiver

Fig. 1 Superheterodyne Receivers for the Doppler Shift Laser Velocimeter

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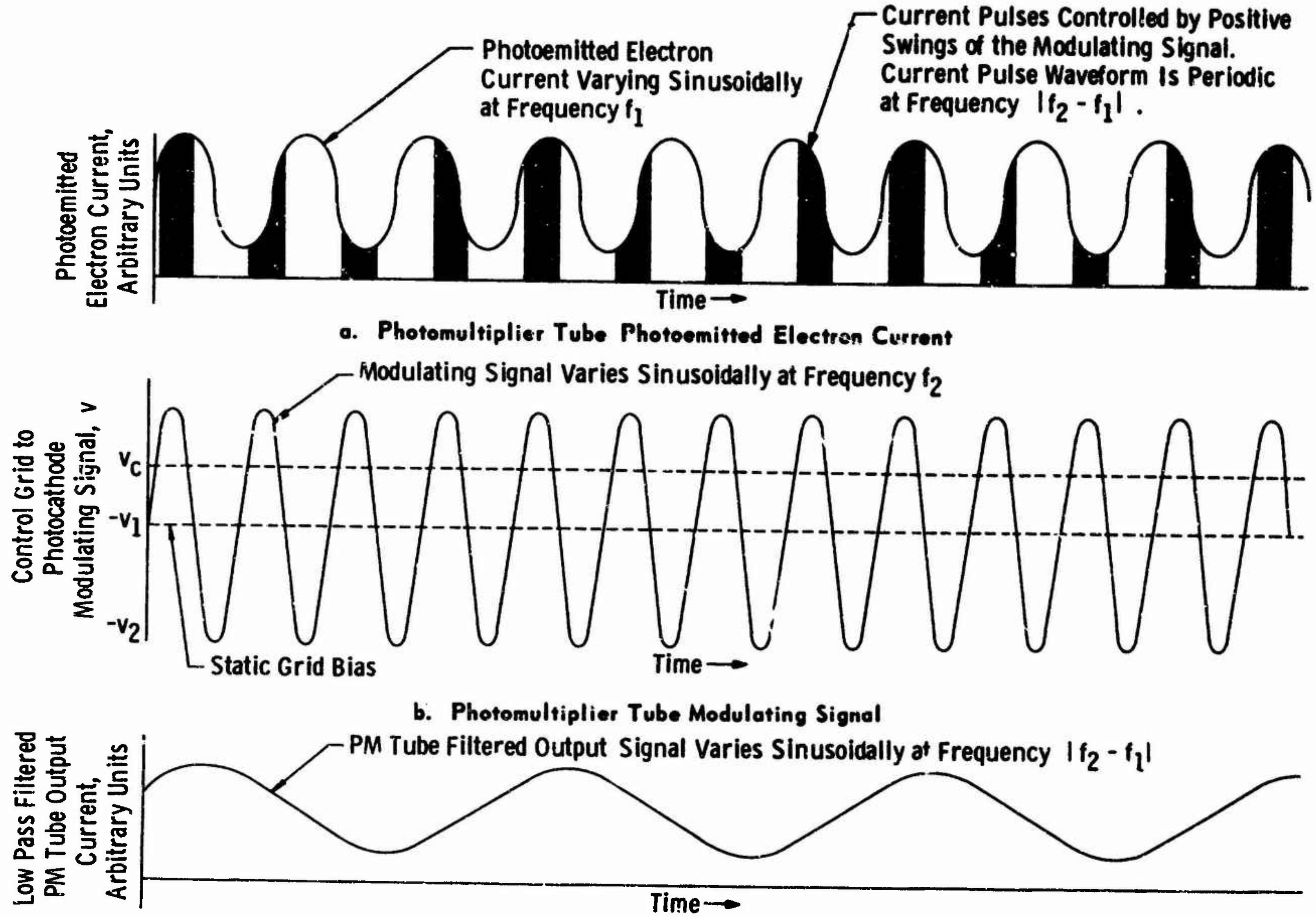


c. Frequency Heterodyned and Filtered Photomultiplier Tube Output Signal

Fig. 2 Graphical Description of Photomultiplier Tube Frequency Heterodyning Process

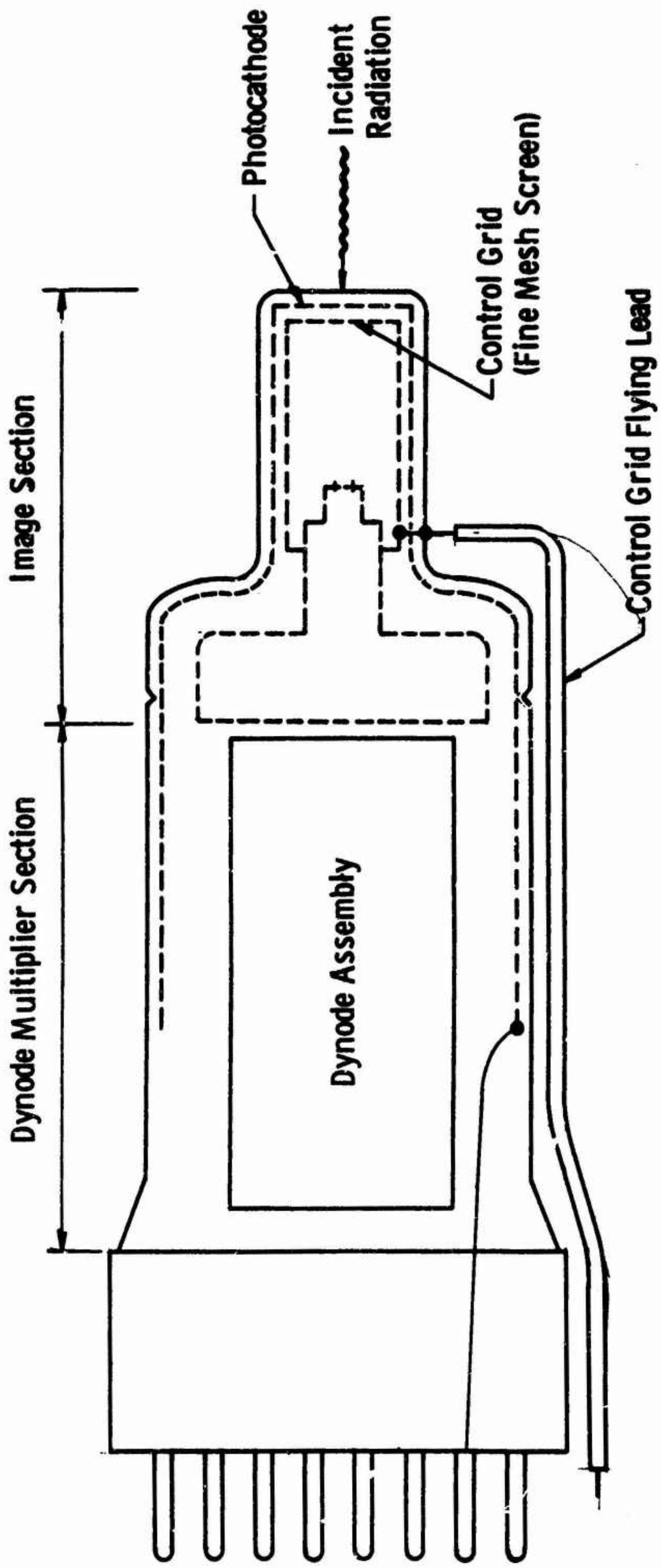


Fig. 3 Photomultiplier Tube, PMI

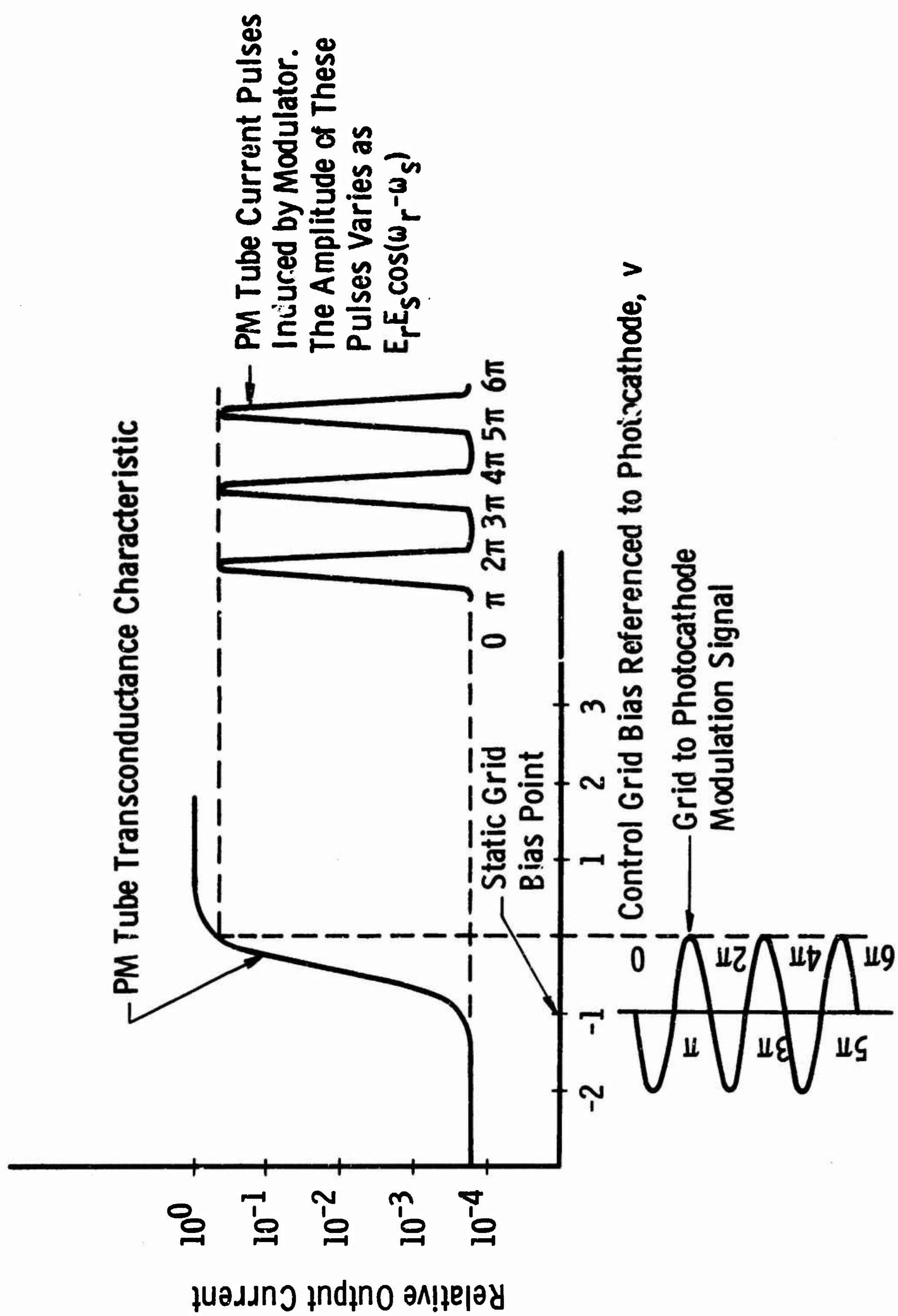


Fig. 4 Photomultiplier Tube Control Grid Modulating Characteristics, PM1

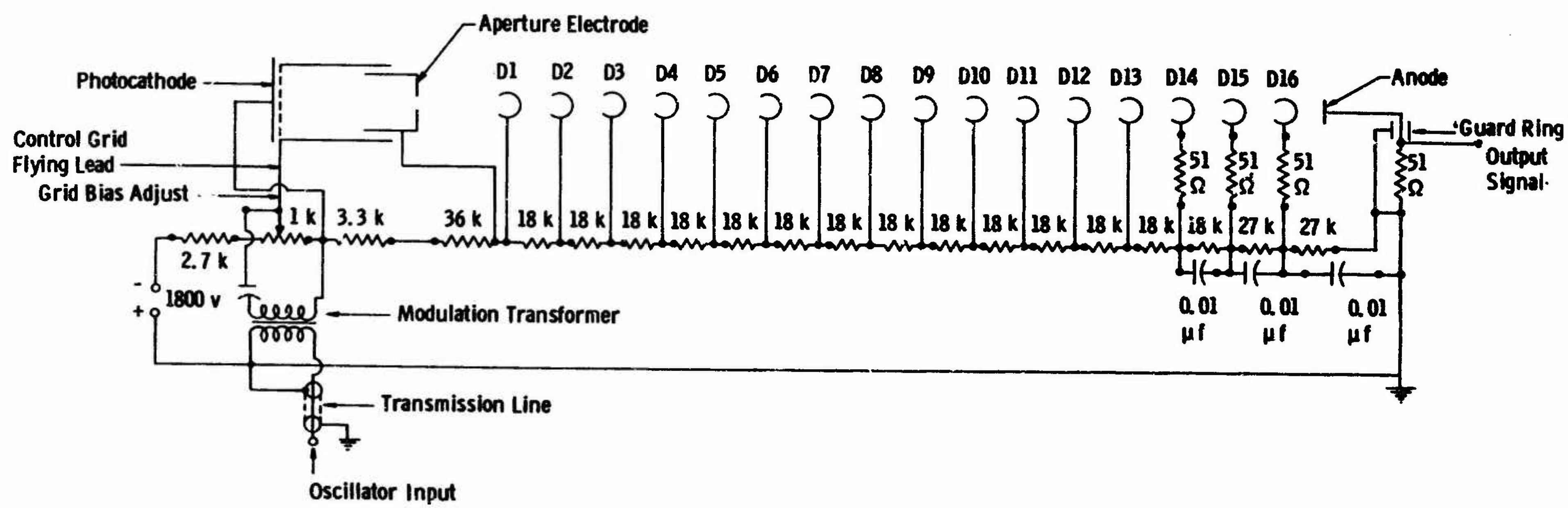


Fig. 5 Photomultiplier Tube Electrical Connections, PM1

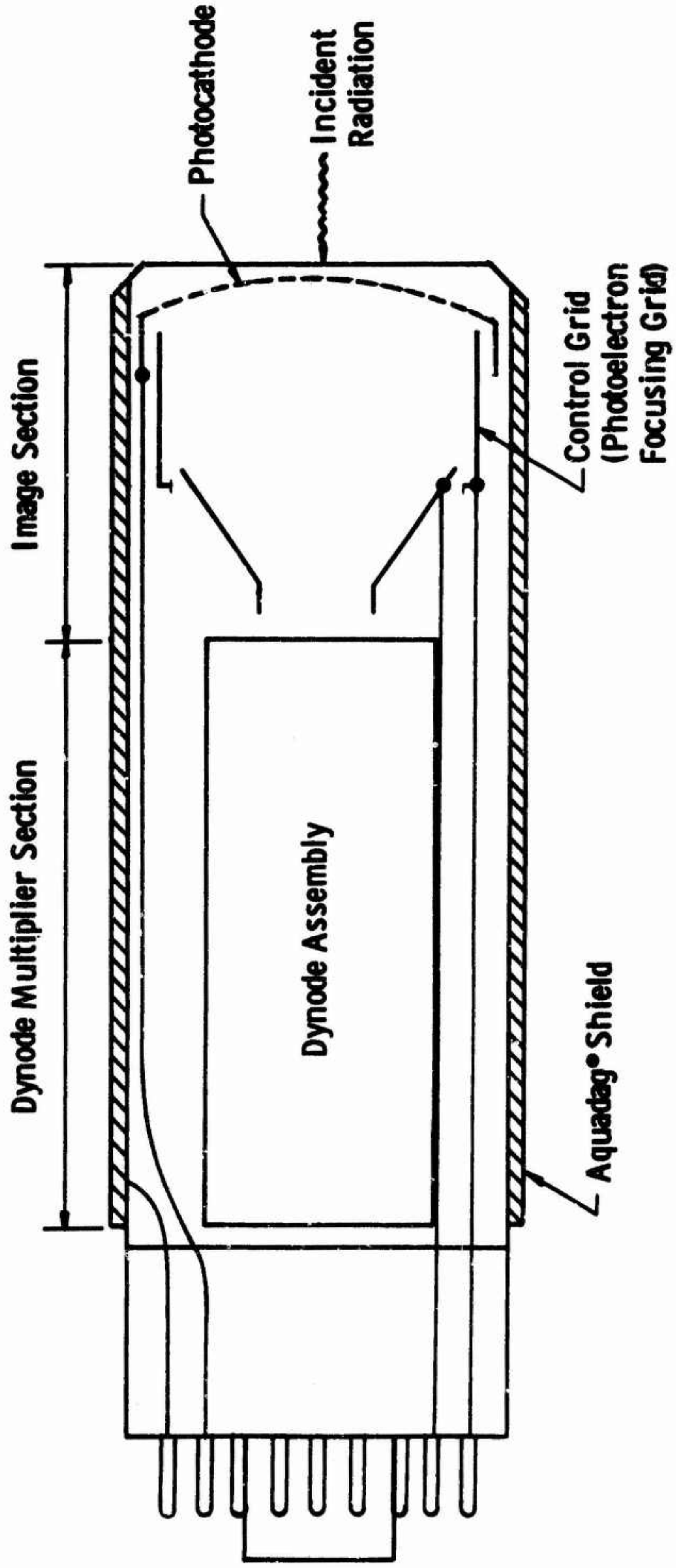
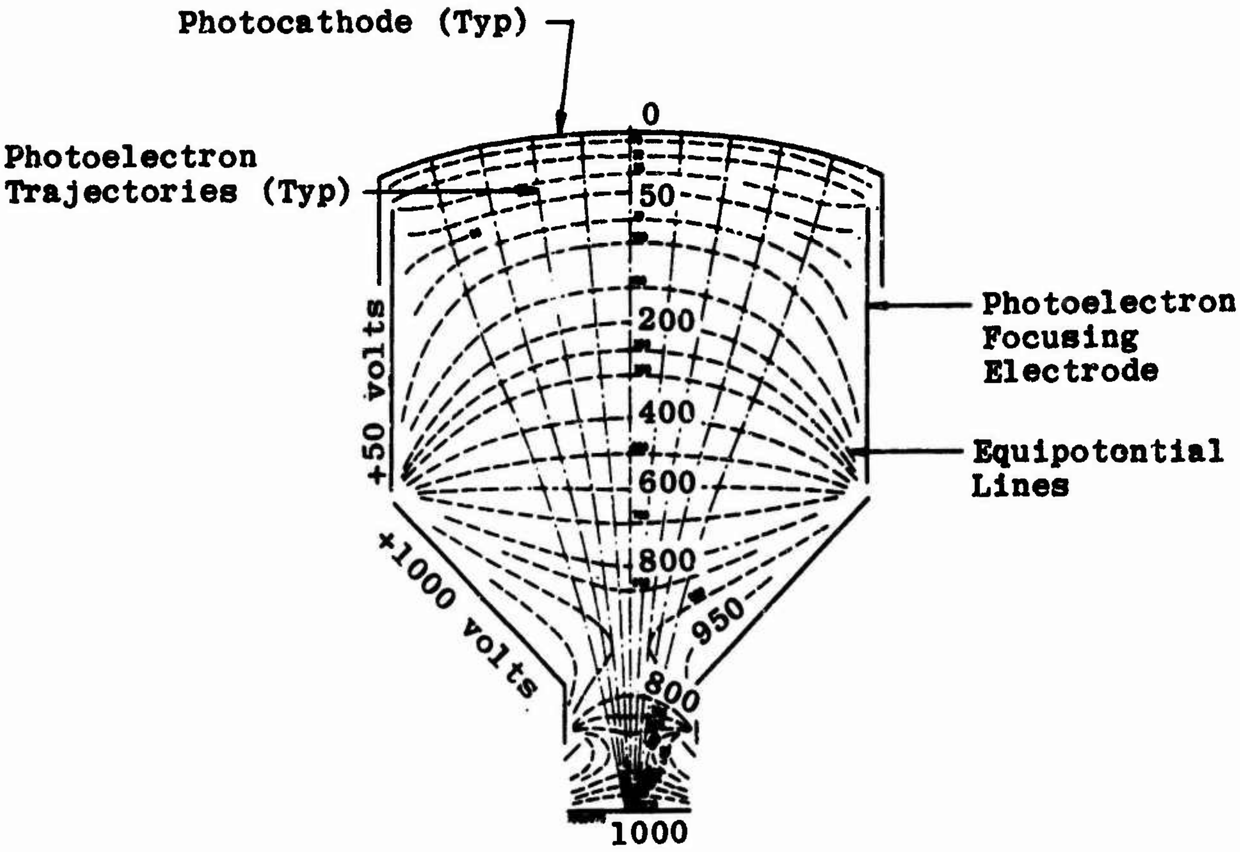
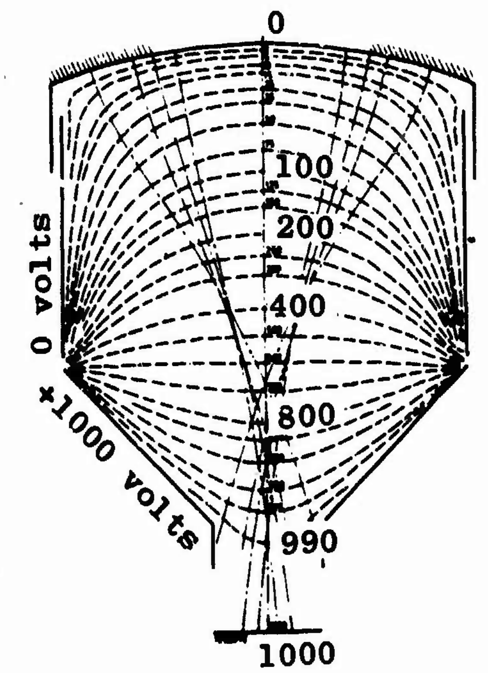


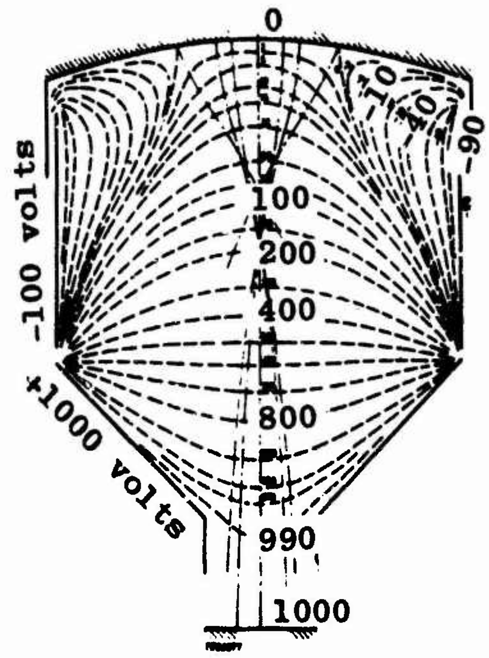
Fig. 6 Photomultiplier Tube, PM2



a. Photoelectron Trajectories for +50-volt Bias

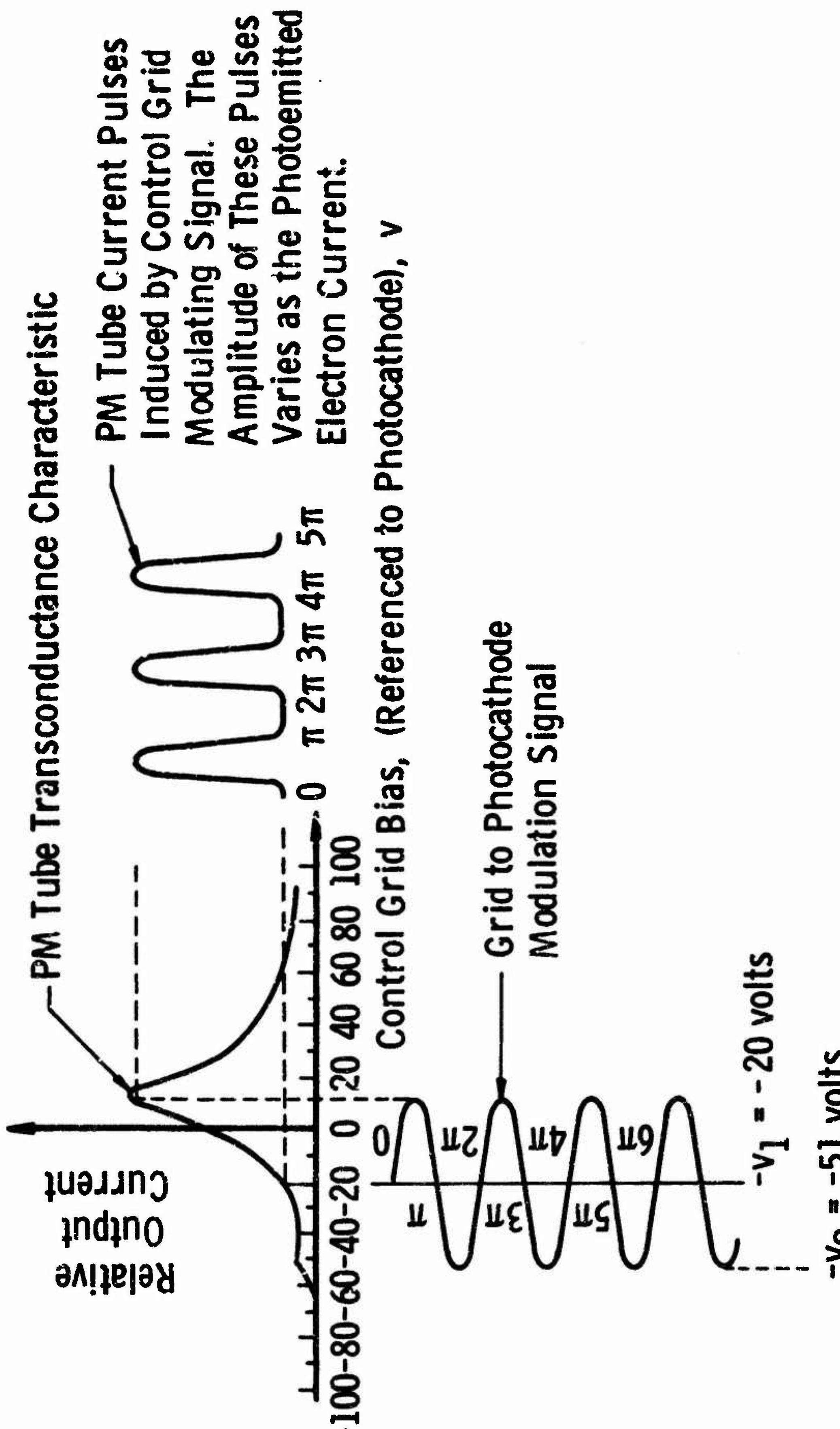


b. Photoelectron Trajectories 0-volt Bias



c. Photoelectron Trajectories for −100-volt Bias

Fig. 7 Photomultiplier Tube Photoelectron Imaging and and Control Grid Characteristics, PM2



d. Control Grid Modulating Characteristics

Fig. 7 Concluded

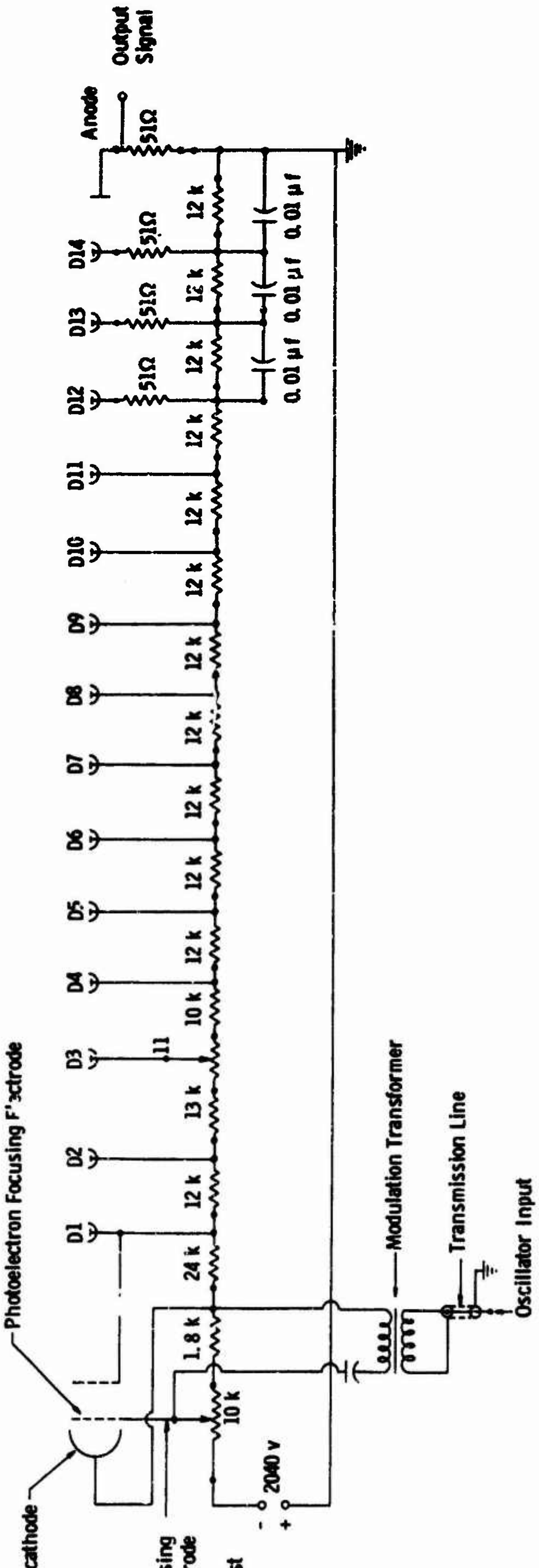


Fig. 8 Photomultiplier Tube Electrical Connections, PM2

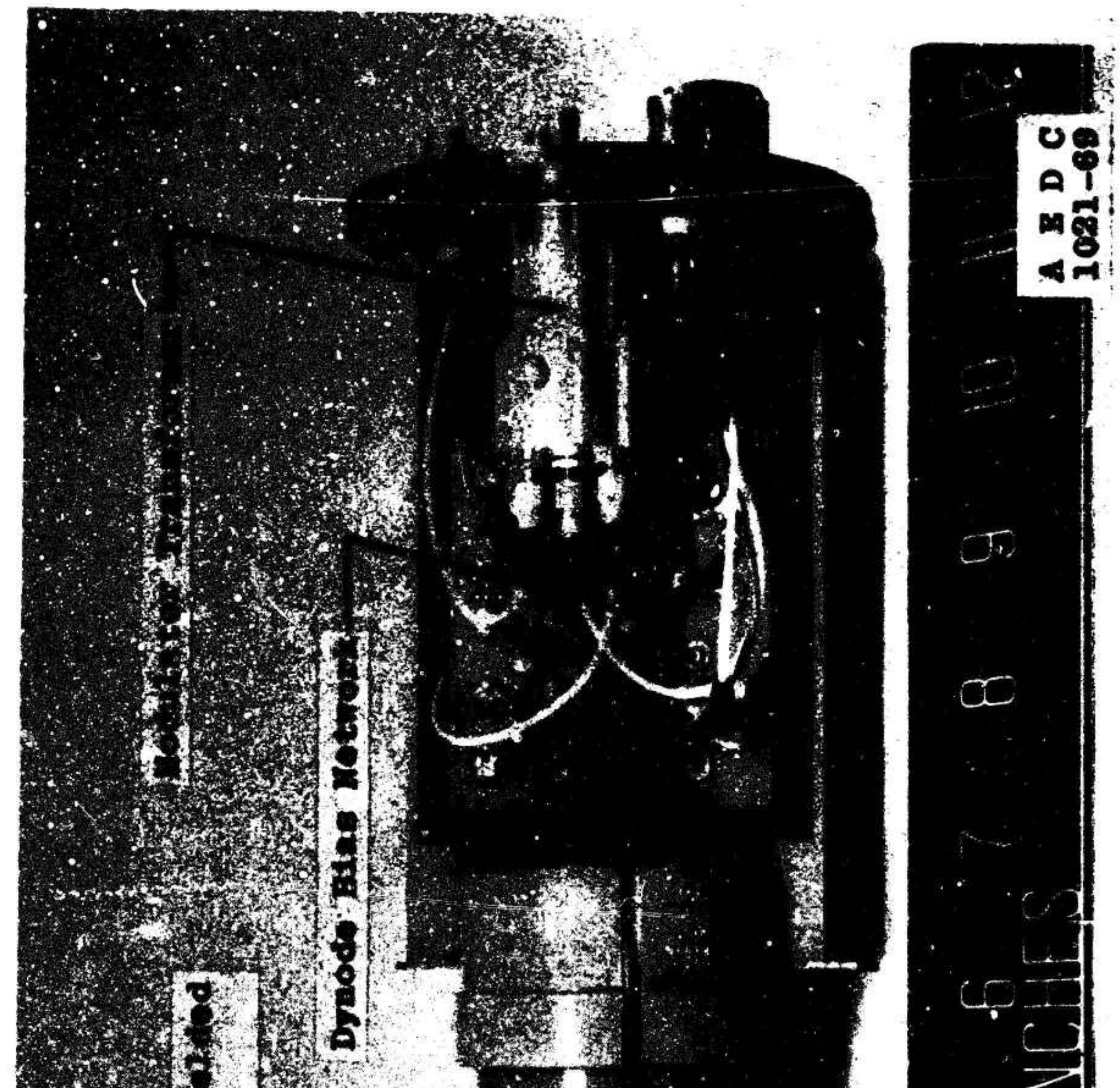


Fig. 9 Photomultiplier Tube Assembly

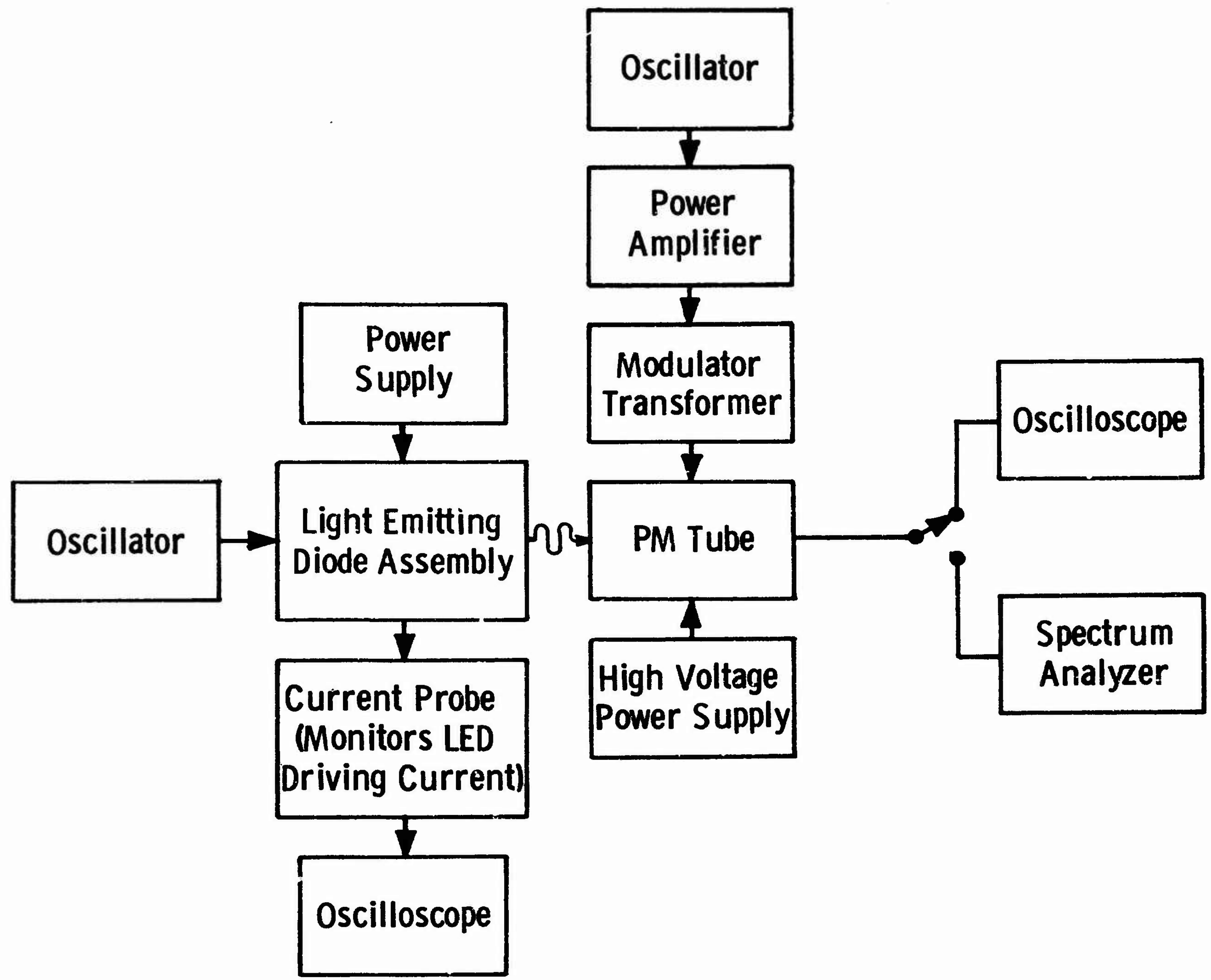


Fig. 10 Photomultiplier Tube Frequency Heterodyne Instrumentation

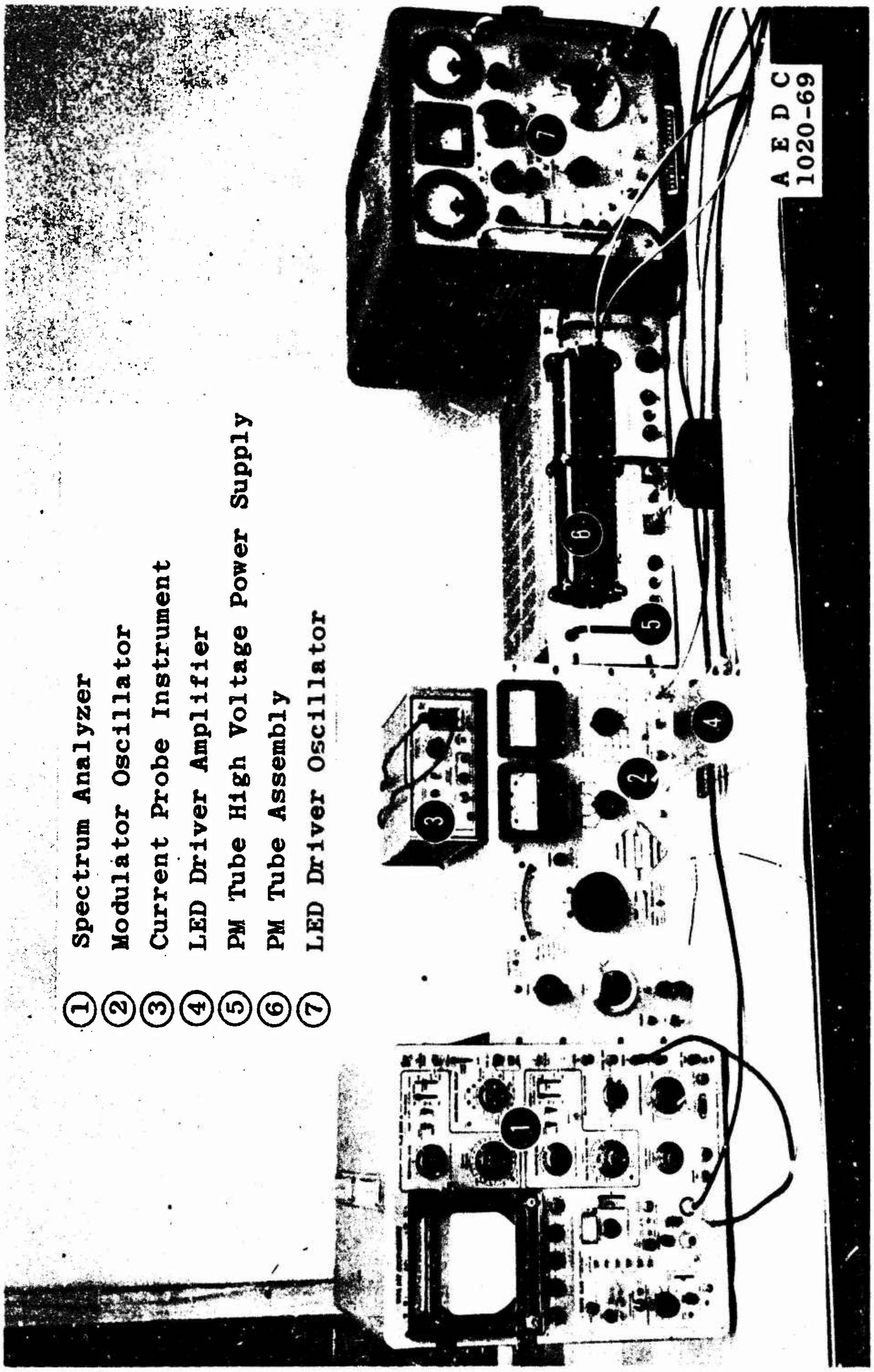
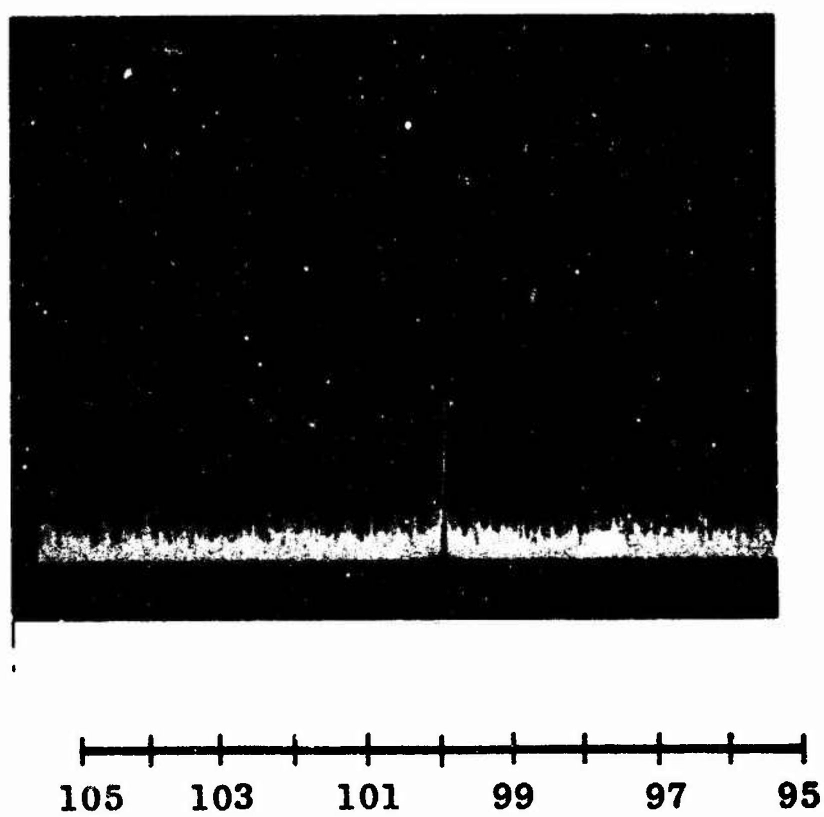


Fig. 11 Experimental Arrangement



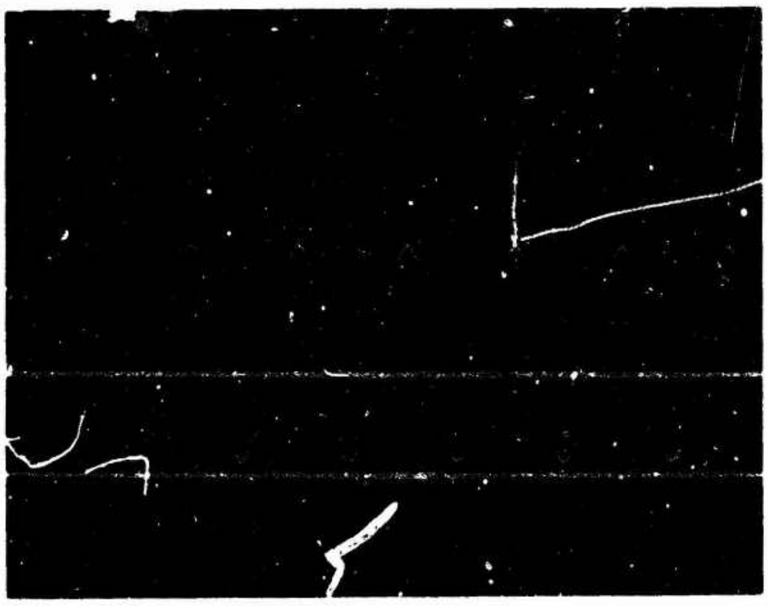
Vertical Scale:
Arbitrary

Horizontal Scale:
1 MHz/cm

Displayed Spectrum
Analyzer
Signal Level Is
-70 dbm

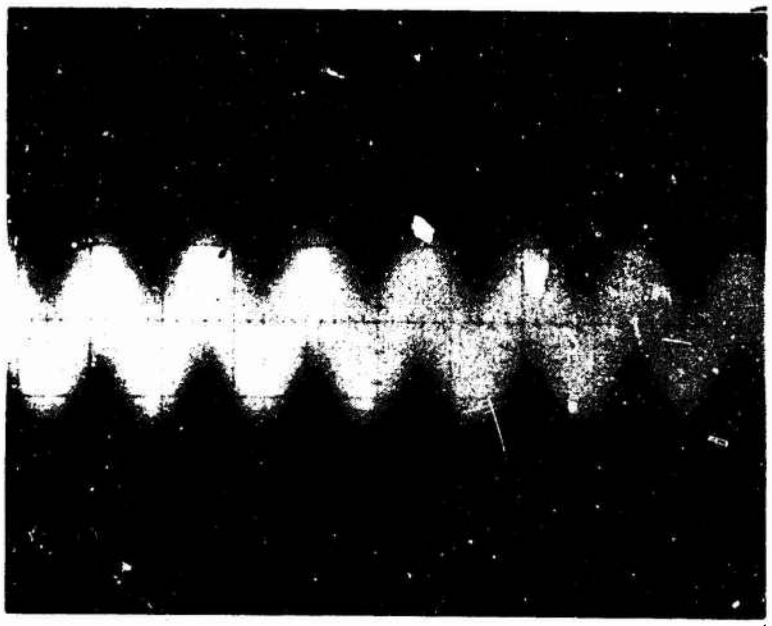
(Spectrum Analyzer Photograph)

Fig. 12 Photomultiplier Tube Response to 100-MHz Sinusoidally Intensity Modulated Light Source, PM1



(Time Domain Oscilloscope Photograph)

Fig. 13 Driving Currents to the Light Emitting Diode

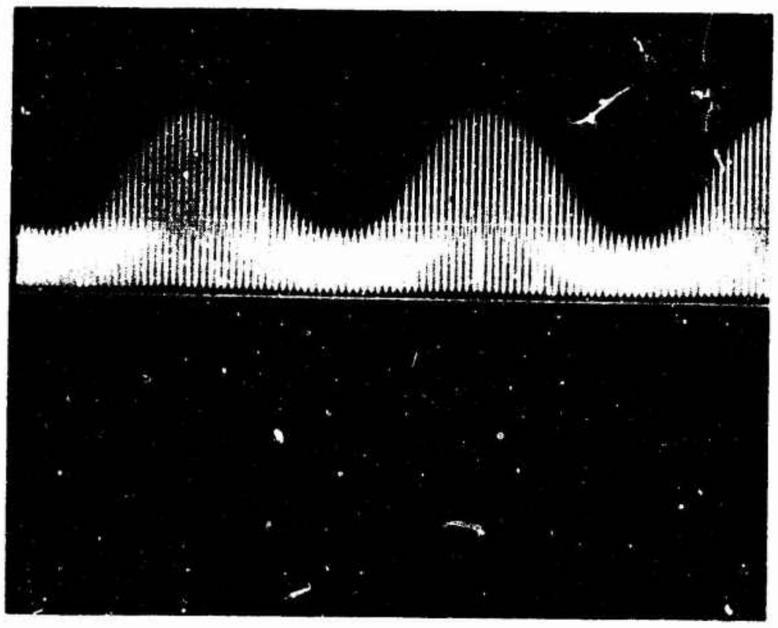


Vertical Scale:
0.020 v/cm

Horizontal Scale:
0.020 µsec/cm

(Time Domain Oscilloscope Photograph)

Fig. 14 Photomultiplier Tube Response to 35-MHz Sinusoidally Intensity Modulated Light Source, PM1



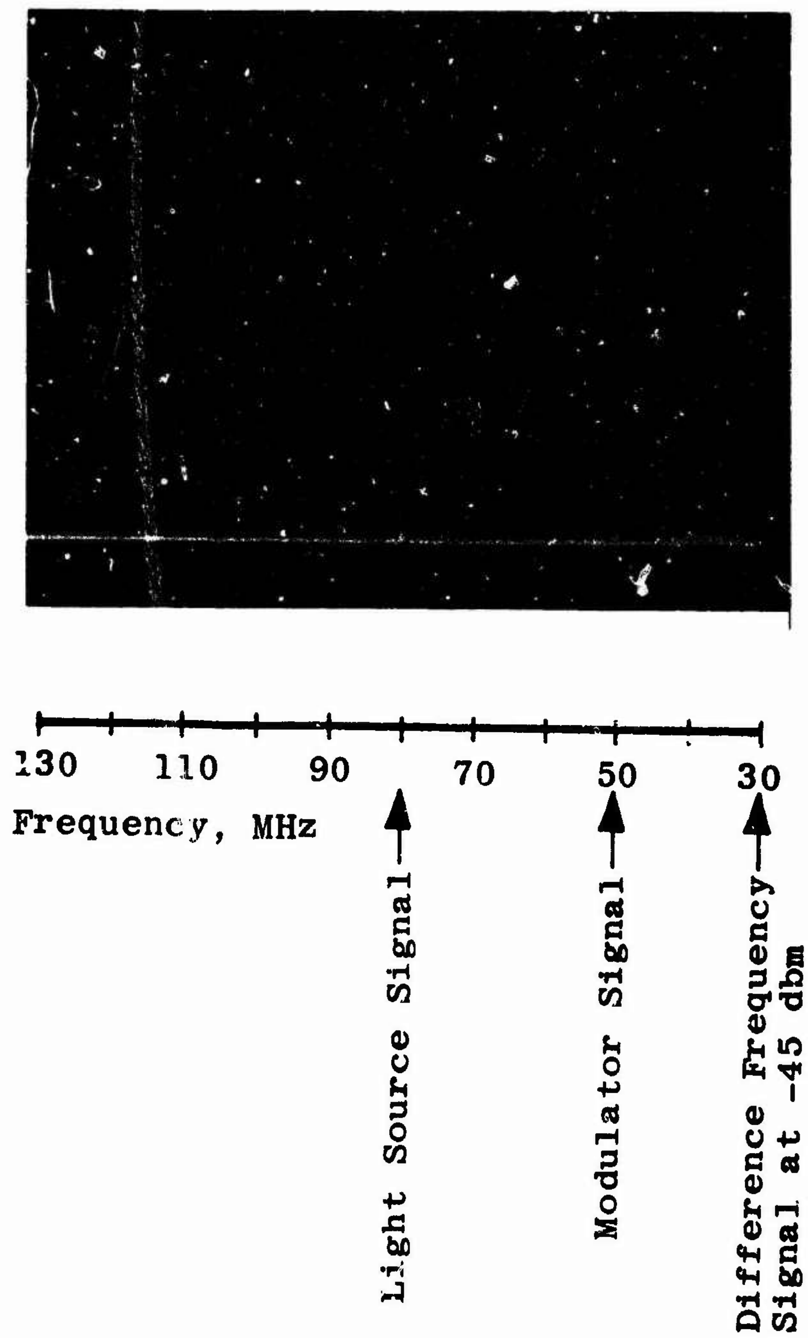
Vertical Scale:
0.1 v/cm

Horizontal Scale:
1 μsec/cm

Envelope Varies
as $E_r E_s \cos(\omega_r - \omega_s)$

(Time Domain Oscilloscope Photograph)

Fig. 15 Photomultiplier Tube Frequency Heterodyne Characteristics at 10 MHz, PM1



Vertical Scale:
Arbitrary
(Linear)

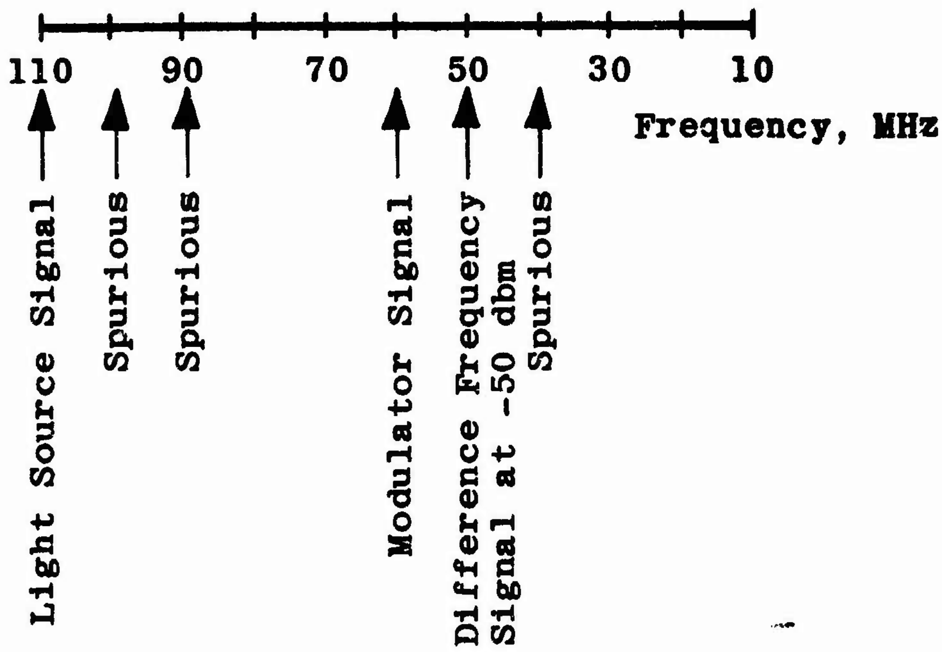
Horizontal Scale:
10 MHz/cm

(Spectrum Analyzer Photograph)

Fig. 16 Photomultiplier Tube Frequency Heterodyne Characteristics at 80, MHz, PM1

Vertical Scale:
Arbitrary
(Linear)

Horizontal Scale:
10 MHz/cm



(Spectrum Analyzer Photograph)

Fig. 17 Photomultiplier Tube Frequency Heterodyne Characteristics at 110 MHz, PM2

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13. ABSTRACT

Photomultiplier tubes with a suitable electrode structure were investigated for use in a superheterodyne-type signal receiver for the Doppler shift laser velocimeter (LV). An oscillator signal impressed upon specially constructed electrodes within the photomultiplier tube produced a signal at a frequency which was the difference between the oscillator and the LV signal frequencies. The high gain of the photomultiplier tube then amplified the difference frequency signal to a usable level. Two different tubes were investigated and found to be useful as heterodyne photomultiplier tube amplifiers. The circuit design, experimental results, and applications are discussed.

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speed indicators						
doppler effect						
superheterodyne receivers						
lasers						

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