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BALANCED DETECTION FOR THE DUAL SCATTER LASER DOPPLER VELOCIMETER

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ARO, Inc.

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NOTICES

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FOREWORD

The work reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65701F, Project 4344, Task 32.

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This technical report has been reviewed and is approved.

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ABSTRACT

Single particles traversing the region of interest produce both a DC term and an AC term as seen by a photomultiplier. The AC term is directly proportional to the particle velocity. In order to accurately determine the frequency of this burst of information, the DC term is rejected by electronic filtering technique. At higher particle velocities the DC rejection becomes difficult, if not impossible, and an alternate technique is necessary. This report describes a balanced detection method to reject the DC term optically without electronic filters. Balanced detection rotates one of the laser beams in a dual scatter laser Doppler velocimeter such that light scattering from the probe volume has the two scattering components 90 deg apart. A polarization-sensitive beam splitter is employed to split the scattered light into two components with one beam undergoing a 90-deg phase shift. Two photomultipliers are used to detect each signal. Inversion of one signal, then adding, rejects the DC term and adds the (now in phase) AC term. System performance and experimental verifications are presented.

CONTENTS

ILLUSTRATIONS

SECTION I
INTRODUCTION

It is highly desirable to operate the laser Doppler velocimeter (LDV) under extremely low seeding conditions because of the many problems encountered with both the test cell requirements and the smoke generation techniques. But this low seeding condition requires a completely different concept for the electronic readout such that a new domain of problems arises for achieving unperturbed velocity information of flow fields.

The ambient particle density found in test cells generally has sufficient seeding for the operation of a dual scatter LDV unit such that velocity information may be obtained from single particles traversing the probe volume. This has been experimentally verified (Ref. 1) in the form of real-time displays of particles traversing the probe volume, Fig. 1. The conversion from the time domain to the frequency domain is generally effected with a frequency spectrum analyzer which depends upon a periodic repetition of information pulses. For single particle analysis, each particle velocity being slightly different from the other, an alternate criterion must be used for data reduction. The technique presently being pursued is the zero crossing technique wherein time is measured for, say, eight cycles to cross a zero reference point. Figure 1 shows the signals associated with this technique. It can be seen that each particle has an AC portion (the velocity information) superimposed on a pedestal (or DC term) which varies greatly with particle size and relative position of the particle traversing the probe volume. At present this pedestal is being removed by an electronic filtering technique. This technique has limitations in the higher frequency region, above 25 MHz, in that the AC term is greatly attenuated.

A new technique is proposed utilizing a balanced detection system to electronically reject the DC term and any other common noise sources, such as the laser beat frequency, and add the AC terms from each photomultiplier tube. In order that the AC term add, a 180-deg phase shift must be effected between the two phototubes such that inversion of one of the signals produces in-phase summation of signals. The technique is discussed in the following section in detail.

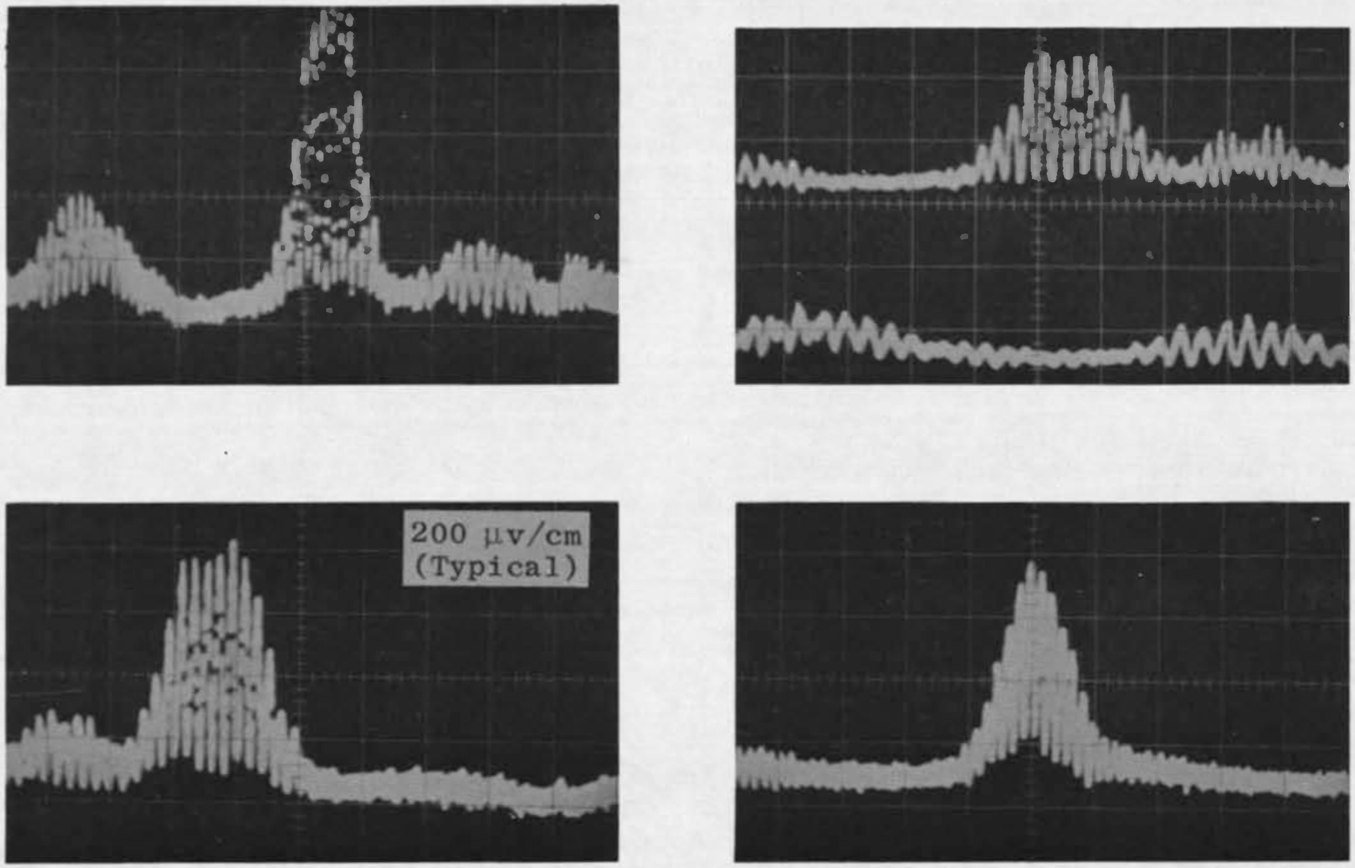


Fig. 1 Single Dust Particle Traversing Probe Volume

SECTION II
THEORY

The fundamental basis for balanced detector operation lies in detecting a Doppler-shifted light beam by two separate detectors and recombining the signals electronically in such a way that common terms in each output are cancelled. A 180-deg phase shift must be effected for one channel such that an inversion (sign change) will again produce in-phase AC information. This mode of operation may be realized by rotating the plane of polarization of one of the two cross beams by 90 deg. Light scattered from each beam will, therefore, also be 90 deg apart in respective polarization. When the two beams[1] are passed through a polarization beam splitter, the two polarized radiations are separated. By rotating this polarization beam splitter to approximately 45 deg, a portion from each oppositely polarized beam is mixed or homodyned to produce the Doppler information.

Terms S(t) and R(t) are the field vectors of the two 90 deg $\pm\ \phi$ polarized beams as shown. The vector components from S(t) and R(t) along the optical axis of the prism are given by E_B and E_C which is easily shown to be

$$E_B = \frac{S(t)}{\sqrt{2}}\left[\cos(\phi - \theta) - \sin(\phi - \theta)\right] + \frac{R(t)}{\sqrt{2}}\left[\cos\theta - \sin\theta\right] \tag{1a}$$

Similarly, for E_C

$$E_C = \frac{S(t)}{\sqrt{2}}\left[\cos(\phi - \theta) + \sin(\phi - \theta)\right] + \frac{R(t)}{\sqrt{2}}\left[\cos\theta + \sin\theta\right] \tag{1b}$$

The coordinate systems of the two polarized beams and prism (beam splitter) assembly are given below.

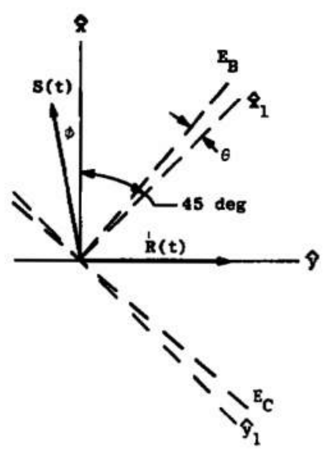
S(t), R(t) - Scattered Radiations

E_B, E_C - Component Fields from S(t) and R(t) along the Two Optical Axes of Prism

$\hat{x}_1$, $\hat{y}_1$ - Coordinate Axis, $\hat{x}$, $\hat{y}$ Rotated 45 deg

θ - Difference between Prism Optical Axis and $\hat{x}_1$, $\hat{y}_1$ Axis

ϕ - Possible Error in S(t) and R(t) Polarization



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[1]In actuality the two beams may be thought of as one beam as is commonly done in the standard dual scatter LDV, i.e., it is thought of as prealigned or self-aligning radiation.

Terms E_B and E_C are the respective electric field components arriving at each phototube. The phototube current is proportional to the Poynting flux time averaged over the optical period which, in turn, is proportional to the real part of $E_B E_B^*$, where the * implies the complex conjugate.

Let α and β be proportionality factors to account for any amplifier imbalance and unequal phototube sensitivity. The phototube current in channel B is

$$I_B = \frac{\alpha}{2}\Big[|S(t)|^2 [1 - \sin 2(\phi - \theta)] - 2 \operatorname{Re} R(t) S^*(t) [\cos \theta - \sin \theta][\cos (\phi - \theta) - \sin (\phi - \theta)] + |R(t)|^2 [1 - \sin 2\theta]\Big] \tag{2a}$$

Similarly for the phototube current in channel C

$$I_C = \frac{\beta}{2}\Big[|S(t)|^2 [1 + \sin 2(\phi - \theta)] - 2 \operatorname{Re} R(t) S^*(t)[\cos(\phi - \theta) + \sin(\phi - \theta)][\cos \theta + \sin \theta] + |R(t)|^2[1 + \sin 2\theta]\Big] \tag{2b}$$

The Re $R(t)\,S^*(t)$ terms represent the homodyned AC term (the velocity information). The $|R(t)|^2$ and $|S(t)|^2$ terms represent the DC term of the homodyning process. Rejection of this DC term may be effected by a subtraction device, in this case a differential preamplifier. For simplicity, let the preamplifier gain be unity, hence the signal output will be proportional to

$$\begin{aligned} V_A(t) = {} & \frac{\alpha}{2}|S(t)|^2 [1 - \sin 2(\phi - \theta)] - \frac{\beta}{2}|S(t)|^2 [1 + \sin 2(\phi - \theta)] \\ & + \frac{\alpha}{2}\, 2\operatorname{Re} R(t) S^*(t) [\cos(\phi - \theta) - \sin (\phi - \theta)] \\ & \times [\cos \theta - \sin \theta] + \frac{\beta}{2}\, 2 \operatorname{Re} R(t) S^*(t) [\cos(\phi - \theta) \\ & - \sin(\phi - \theta)] [\cos \theta + \sin \theta] + \frac{\alpha}{2} |R(t)|^2 [1 - \sin 2\theta] \\ & - \frac{\beta}{2} |R(t)|^2 [1 + \sin 2\theta] \end{aligned} \tag{3}$$

This equation may be simplified to

$$\begin{aligned} V_A(t) = {} & \frac{|S(t)|^2}{2} \{(\alpha - \beta) + \sin 2(\phi - \theta) [\alpha + \beta]\} \\ & + \operatorname{Re} R(t)S^*(t) [\cos (\phi - 2\theta) (\alpha + \beta) \\ & + \sin \phi (\beta - \alpha)] + \frac{|R(t)|^2}{2} [(\alpha - \beta) + \sin 2\theta(\alpha + \beta)] \end{aligned} \tag{4}$$

Equation (4) represents the output from the adding device shown in Fig. 2. For the case when S(t) and R(t) are exactly 90 deg apart in this polarization plane, $\phi = 0$, one term in Eq. (4) drops. Adjustments of the electronic parameters allow one to make $\alpha \approx \beta$ such that two more

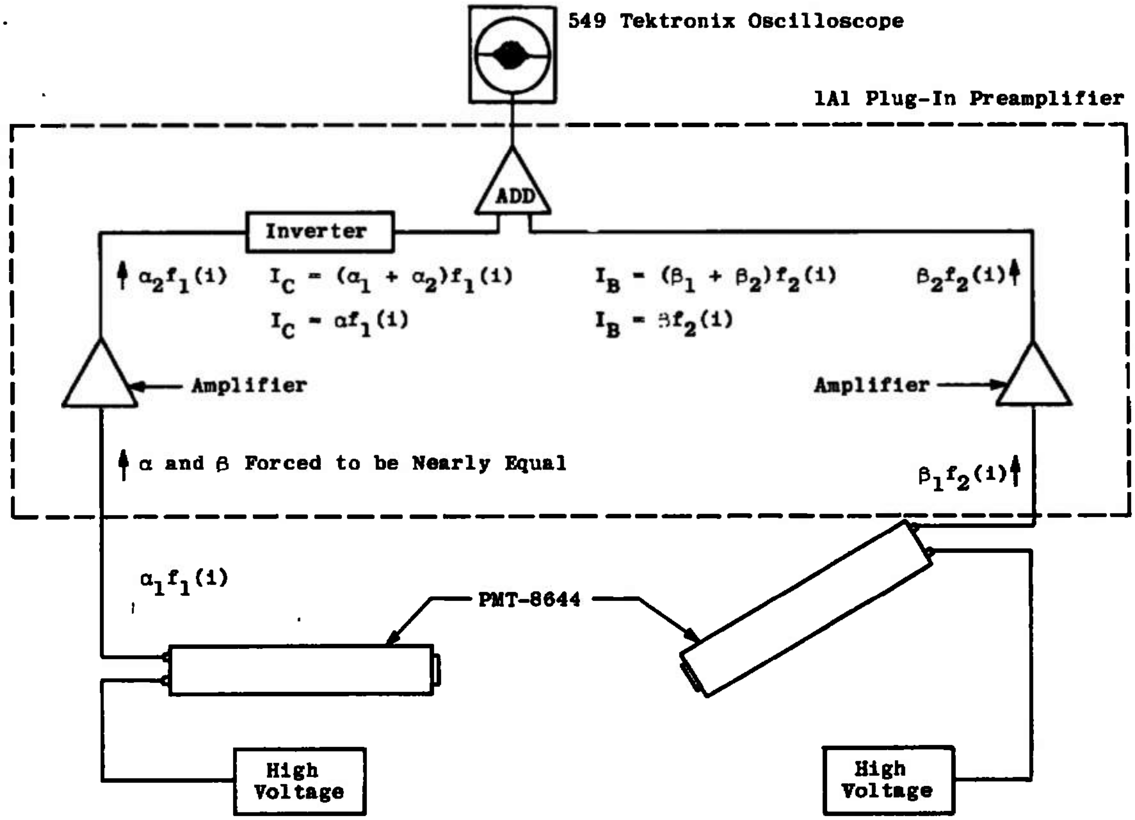

Fig. 2 Schematic of Instrumentation

terms drop from the equation. The remaining terms may be removed by adjusting the prism assembly to $\theta = 0$, leaving the homodyned term of

$$V_A(t) = (\alpha + \beta) \, \mathrm{Re} \, S(t) \, R^*(t) \tag{5}$$

The adjustment of θ is effected by observing either the separate channels and adjusting for identical waveforms or by observing $V_A(t)$ for a symmetrical waveform.

The Eqs. (2a) and (2b) must, of course, reduce to the form of Eq. 5

$$V_C(t) \propto \mathrm{Re} \, S_C(t) \, R_C^*(t) \quad \text{and} \quad V_B(t) \propto \mathrm{Re} \, S_B(t) \, R_B^*(t)$$

One channel originated from transmitted scattered radiation through the prism and the other channel originated from reflected radiation of the birefringent interface. The reflected radiation necessarily has a π phase shift in the optical frequency of the scattered light. It is therefore only necessary to show that this π optical phase shift necessarily produces a π Doppler phase shift. Terms R(t) and S(t) may be written in terms of the optical frequencies f_o and propagation constant, k_o, such that for the dual scatter system we have

$$R(t) = R(t)e^{i[(k_o + k_i)x + 2\pi(f_o + f_1)t + \pi]}$$
$$S(t) = S(t)e^{i[(k_o + k_2)x + 2\pi(f_o + f_2)t + \pi]} \quad (6)$$

having included the optical phase shift of π for the reflected radiation. The voltage in the channel receiving the reflected light is proportional to

$$R(t)S^*(t) = R(t)e^{+i[(k_o + k_1)x + 2\pi(f_o + f_1)t - \pi]} S^*(t)e^{-i[(k_o + k_2)x + 2\pi(f_o - f_2)t + \pi]} \quad (7)$$

Rearranging terms, cancelling the k_o terms and f_o terms, Eq. (7) becomes

$$R(t)S^*(t) = R(t)\,S^*(t)e^{i[(k_1 + k_2)x + 2\pi(f_1 - f_2)t + \pi]} \quad (8)$$

The exponential term may be written in terms of $e^{i(x)} = \cos x + i \sin x$ and since only the real part is considered, Eq. (5) becomes

$$S(t)\,R(t) \cos[k_D x + 2\pi f_D t - \pi] \propto V_C(t) \quad (9)$$

Equation (9) states that $V_C(t)$ varies sinusoidally with frequency f_D and shifted in phase by 180 deg. Term $V_B(t)$ is the transmitted information having no optical phase shift of π. Subtracting the channels gives

$$V_C(t) - V_B(t) \propto \cos(f_D t + \pi) - \cos f_D t \quad (10)$$

Clearly, when adding $V_C(t) + V_B(t)$ the Doppler information cancels, but the subtraction makes $V_A(t)$ equal to

$$V_C(t) - V_B(t) = |2 \cos[f_D(t)]| \quad (11)$$

i.e., the Doppler information is doubled since the two sinusoidal waves are in phase.

SECTION III
EXPERIMENTAL DETAILS

3.1 OPTICAL COMPONENTS

The optical configuration consists of a standard dual scatter, one velocity component, laser velocimeter operated in the backscatter, off-axis mode. To effect the balanced detector component, a 90-deg polarization rotator was placed in one of the parallel beams before the focusing lens. Figure 3 illustrates, schematically, the experimental agreement. The primary differences from that of a standard LDV come after the entrance aperture. Light passing through the 440-micron aperture is collimated by a modified microscope objective. The collimated beam is then passed through a Glan-Air prism oriented 90 deg relative to the polarization of the scattered light. This prism splits the collected light into two beams which are detected by the two photomultipliers. The scattered light was produced by passing an 8-micron-diam wire through the geometric probe volume. To align the collecting optics to the corresponding geometric probe volume, the entire assembly, from the aperture back, had to be moveable in the x-y-z direction. This produced a difficult alignment problem for the aperture, collimating lens, and prism assembly. The difficulty was solved by mounting the aperture, collimating lens, and prism assembly on an independent x-y-z traverse (modified Jodon spatial filter) such that its alignment could be effected independent of the probe volume x-y-z frame unit. Figure 4 is a photograph of this assembly. The prism assembly could be rotated on its optical axis in order to allow variations of θ for the DC rejection of Eq. (4).

An Argon ion laser, having 4880-Å wavelength, was used since the available optical components were specifically designed for that wavelength.

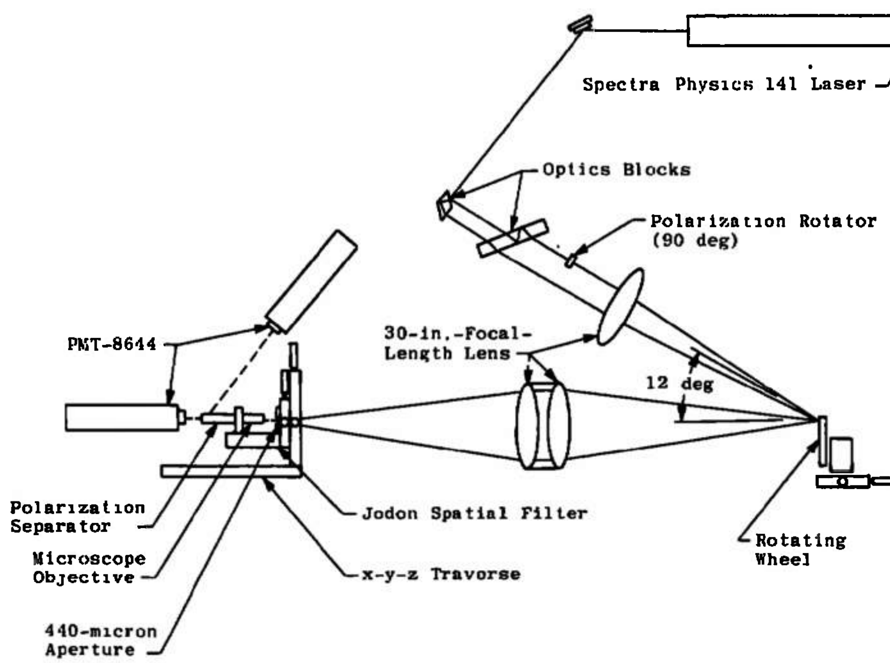

Fig. 3 Schematic of Optic Components

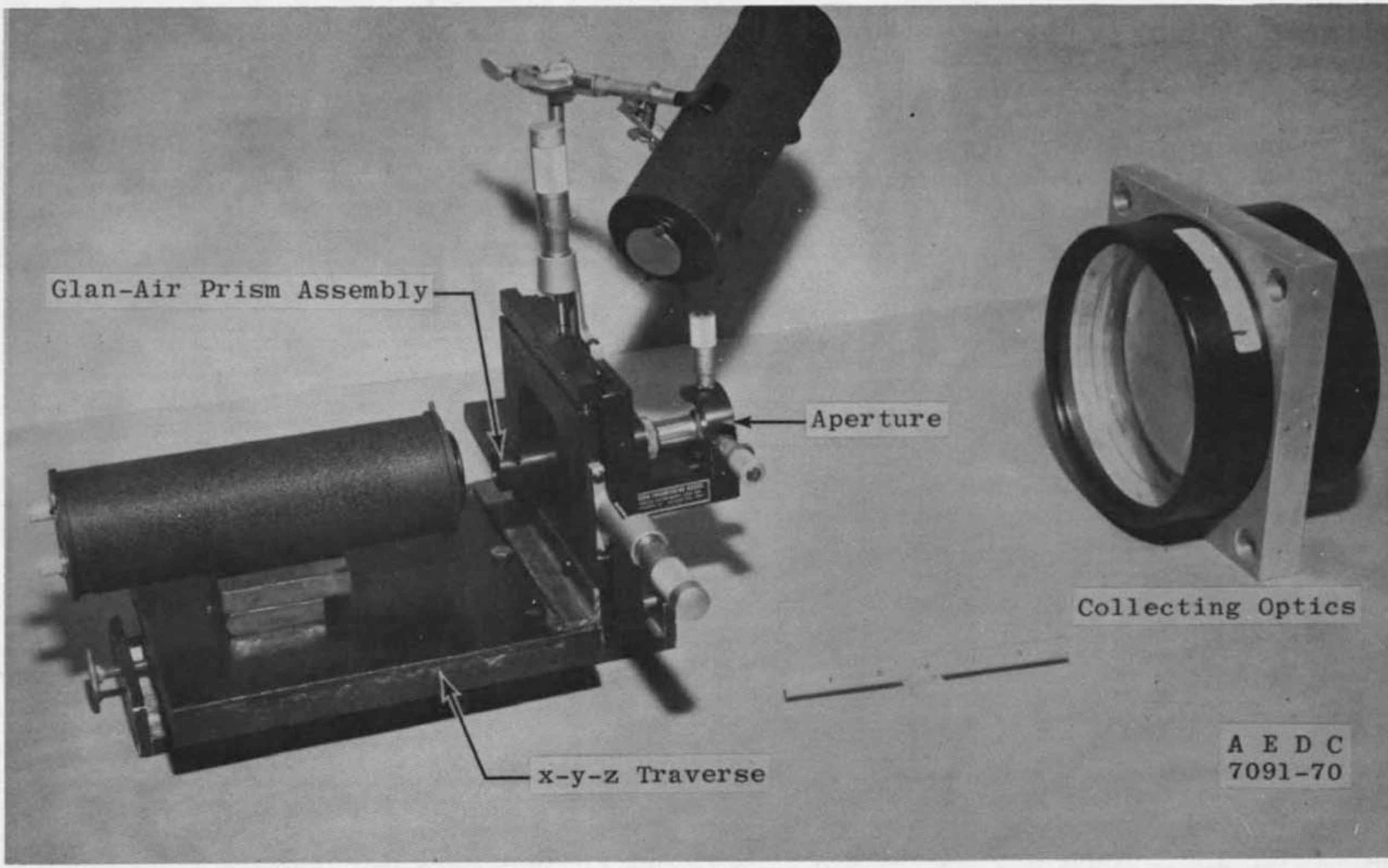

Fig. 4 Photograph of Input Optics

3.2 ELECTRONICS CONFIGURATION

Two 8644 photomultiplier tubes were chosen for nearly equal sensitivity and gain. This was necessary to ensure nearly equal α and β in Eq. (4). Two separate high voltage supplies were needed to allow independent gain adjustment. A similar problem was found with the two amplifiers. The Tektronix 1A1 preamplifier was used for separate amplification, sign change of one input, and addition of the two inputs before being displayed on the oscilloscope. Figure 2 schematically represents the electronic configuration used in the experiment. Adjustments of high voltage and amplifier gain enabled practically equal α and β adjustments.

3.3 EXPERIMENTAL RESULTS

A signal was obtained by passing a small wire through the geometric probe volume. The technique was chosen since repetition of the same information pulse allowed accurate alignment of the velocimeter system.

Alignment was effected with only one channel. The collimating microscope lens and aperture were aligned first such that light passing through the aperture was collimated before passing through the polarization separator. Once this alignment was effected, no further adjustment was required. The remaining alignment was therefore reduced to the standard dual scatter LDV alignment procedure. Since the phototubes have a 1-in. photocathode surface, small adjustments of the x-y-z traverse did not require additional phototube alignment.

Each phototube output was displayed separately on the oscilloscope to ensure proper alignment of each channel before being summed. Adjustment of the prism assembly produced similar waveforms in each channel which occur when $\theta \rightarrow 0$. Figure 5 shows the two channels with the top trace already inverted. Notice particularly the 180-deg phase shift between the two channels. Subsequent addition clearly rejected the DC pedestal of the two channels producing the AC Doppler information near some zero base line. The second set of photographs was made at another point in the probe volume with similar results.

As always, proper alignment is important. Figure 6 represents a misalignment of one channel. The subsequent addition of these two channels produced a badly distorted waveform, as would be expected. The second set of photographs shows a better balance between channels. The balance between channels is effected by proper alignment of probe volumes, prism orientation, amplifier gain, and phototube high voltage supply.

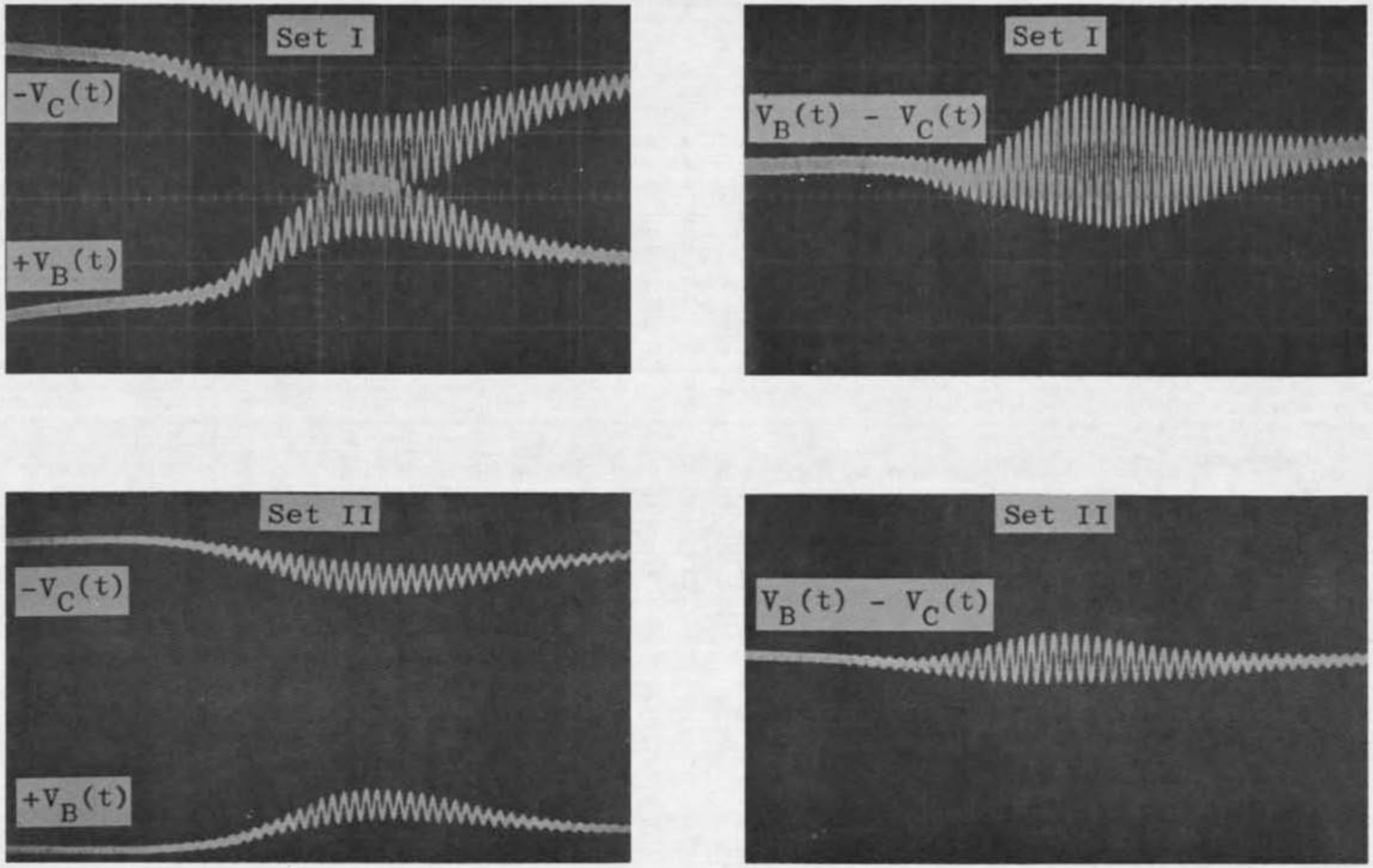

Fig. 5 Verification of Balanced Detection

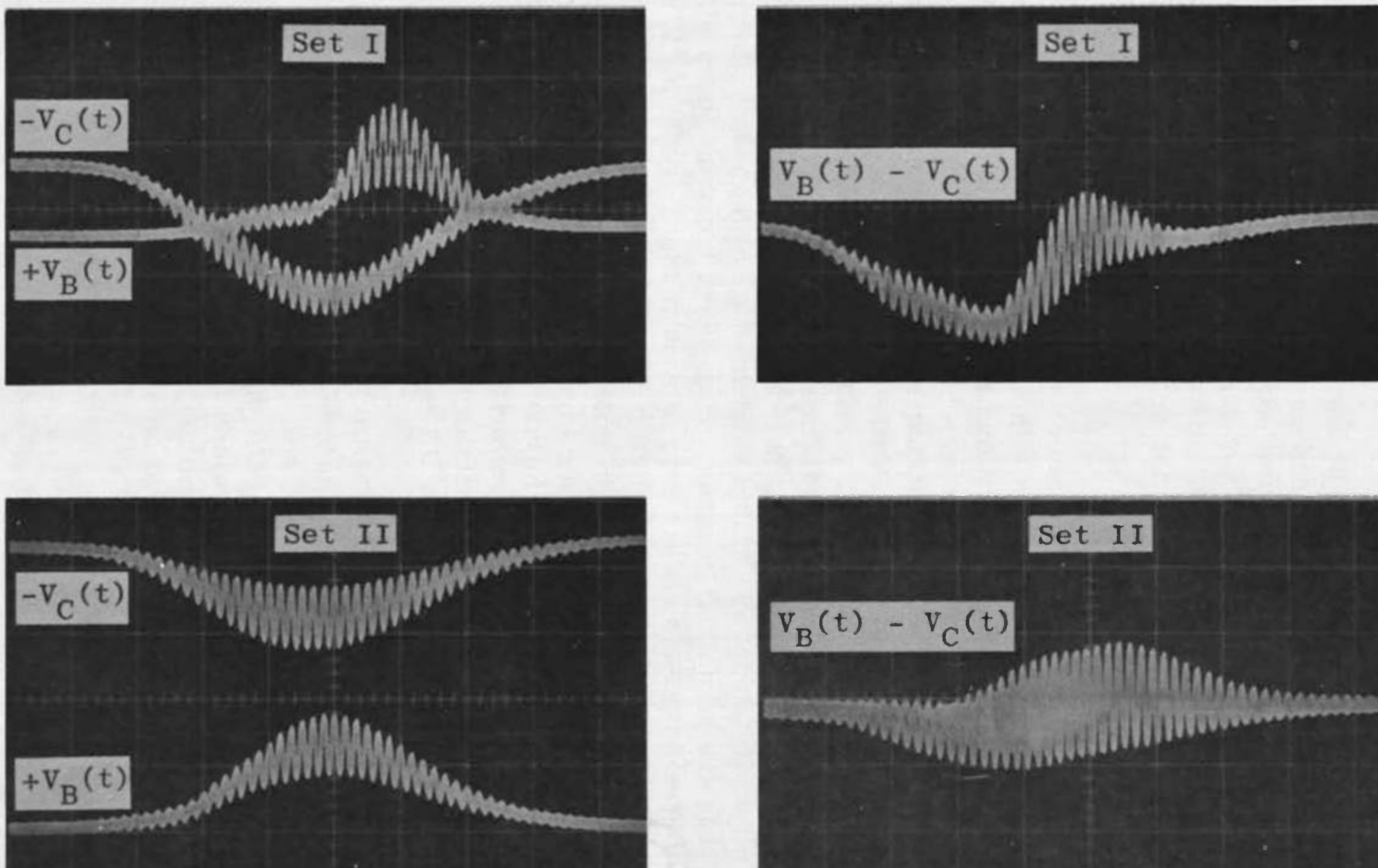

Fig. 6 Misaligned Inputs of Balanced Detector

SECTION IV
DISCUSSION

It is assumed that once proper alignment is obtained variations of the particle path, in the probe volume, will have no effect on the balance between the two channels. The light scattering phenomenon is assumed to be nearly equal for light scattered from the two oppositely polarized beams. Visual inspection clearly indicated this was not the case. This variation in intensity is assumed to reduce the homodyning efficiency only, without loss of balance between the two channels.

Two distinct disadvantages should be pointed out. The homodyning is effected at the prism—not at the geometric probe volume as in standard LDV units. This means that the collected radiation is affected by wave front distortions up to the prism. Another disadvantage is that, at this time, this balanced detector scheme is usable for one-component systems only.

This technique will be incorporated into a one-component LDV unit for the sole purpose of complementing the pulse data electronic readout.

The geometry of the two separated beams from the Glan-Air prism is highly impractical; hence a Wollestrom prism will be incorporated into a housing that contains both phototubes.

An optical discrimination based on the differential delay between two optical paths has been discussed in Ref. 2. This technique is frequency dependent, but means to increase the frequency bandwidth are also discussed.

Another possibility that might be practical is to extract two signals from two separate dynodes of the phototube. This would mean that all standard LDV units would be able to operate in the balanced detector mode. Also, a two-component system would require only two phototubes instead of four.

Beam splitters have been used for balanced detection (Ref. 3), but it is pointed out that the ordinary laboratory beam splitter does not impose the relative phase relation attributable to losses of the reflecting surfaces. The very thin plastic pellicle beam splitters have been successfully used for balanced mixer experiments.

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3. Waite, T. "A Balanced Mixer for Optical Heterodyning: The Magic T Optical Mixer." Proceedings of IEEE, December 17, 1965.

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