

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

DEVELOPMENT TESTING AND APPLICATION OF A
THREE-DIMENSIONAL LASER DOPPLER VELOCIMETER
FOR THE MEASUREMENT OF GAS FLOWS

HAYES INTERNATIONAL CORPORATION

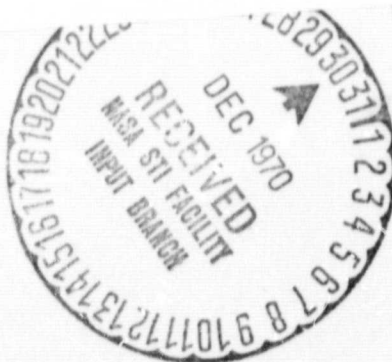
Birmingham, Alabama

ENGINEERING REPORT NO. 1678

April 1970

FACILITY FORM 602

N71-14048	
(ACCESSION NUMBER)	(THRU)
104	63
(PAGES)	(CODE)
CR 102948	16
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)



INTERNATIONAL CORPORATION

BIRMINGHAM, ALABAMA

16

DEVELOPMENT TESTING AND APPLICATION OF A
THREE-DIMENSIONAL LASER DOPPLER VELOCIMETER
FOR THE MEASUREMENT OF GAS FLOWS

HAYES INTERNATIONAL CORPORATION

Birmingham, Alabama

ENGINEERING REPORT NO. 1678

April 1970

By

C. E. Fuller

This work was sponsored by Marshall Space Flight Center
under Contracts NAS8-21527 and NAS8-21162.

TABLE OF CONTENTS

Section		Page
1. 0	INTRODUCTION	1
2. 0	THE LDV SYSTEM	3
2. 1	THREE-DIMENSIONAL LDV INSTRUMENT	3
2. 2	LASER EQUIPMENT	6
2. 3	ASSOCIATED OPTICS	9
2. 4	ELECTRONIC SIGNAL PROCESSING EQUIPMENT	11
2. 5	SYSTEM MEASUREMENTS	16
	2. 5. 1 Scattering Volume	17
	2. 5. 2 Path Length Equalization	19
	2. 5. 3 Electro-Optical Considerations	20
	2. 5. 4 Frequency Tracker	22
3. 0	TRACER SYSTEMS	24
3. 1	TWO-PHASE FLOW CONSIDERATIONS	24
3. 2	TRACER PARTICLES AND INJECTION TECHNIQUES	26
3. 3	TECHNIQUES FOR TRACER PARTICLE SIZE AND CONCENTRATION MEASUREMENTS	34
4. 0	FLOW FIELD MEASUREMENTS	39
4. 1	BASE FLOW MEASUREMENTS FOR A CLUSTERED ENGINE MODEL	39
4. 2	SUBSONIC FREE JET MEASUREMENTS	45
4. 3	SUPERSONIC WIND TUNNEL MEASUREMENTS	49
5. 0	CONCLUSIONS	57
	REFERENCES	59
	TABLES	60
	FIGURES	62

1.0 INTRODUCTION

This report describes the work which has been conducted in the development and application of a three-dimensional laser Doppler velocimeter (LDV) system for the measurement of local mean and fluctuating gas velocities with high spatial and temporal resolution. This system uses optical instrumentation to remotely gather laser light which has been directed into jet or wind tunnel flows. Optical heterodyning is used to detect the Doppler frequency shift in the laser light which occurs when the light is scattered by small tracer particles within the flow. This Doppler frequency shift is mathematically related to the velocity of the particle, the wavelength of the laser light, the angular arrangements of the incident and scatter light, and the angle between the incident light and the velocity vector.

The LDV system described in this report is capable of simultaneously measuring three Doppler frequency shifts from a given point in a flow field. These three Doppler frequencies along with the angular relations between the system and the flow field are used to determine the velocity magnitude and direction of the tracer particle. If the particle is sufficiently small (submicron) then the particle velocity and gas velocity can justifiably be assumed to be equal.

Measurements conducted with the LDV system during this program have demonstrated the ability of the LDV system to make three-dimensional mean velocity measurements in a supersonic wind tunnel flow field, and to make one-dimensional turbulence measurements in subsonic free-jet flow. These flow measurements along with the developmental measurements concerned with the optimization of the system, are presented. Each part of the LDV system, i.e., the LDV instrument, the tracer system, the electronic signal processing systems, the laser equipment, and the associated optics, is described and related to the operation of the entire system. Many measurements concerned with the performance of the system are presented and the

system modifications defined by these measurements are described. Finally the accomplishments of the program are summarized and the conclusions listed.

2.0 THE LDV SYSTEM

The laser Doppler velocimeter system is considered to be composed of all the equipment necessary for making a gas velocity measurement by measuring the Doppler frequency shift. This equipment includes a three-dimensional LDV instrument, a laser, accessory optical components, and electronic signal processing equipment. Each of these components of the LDV system are described in the following segments of this section. Along with the description segments, a segment is also included which discusses the measurements that were conducted to analyze problems associated with the LDV system. An integral part of the LDV system, which is not included in this section, is the tracer systems which inject small scattering particles into a gas flow. Due to the scope and complexity of the problems which were encountered with the tracer systems, a separate section was considered necessary.

2.1 THREE-DIMENSIONAL LDV INSTRUMENT

The three-dimensional LDV instrument houses the optical components needed to collect three Doppler frequency shifted light beams (scatter beams) and the reference or local oscillator (LO) beam. The purpose of the instrument is to direct the scatter and LO beams simultaneously onto the photosensitive surface of a photodetector such as a photomultiplier tube. The intrinsic square-law response of the photodetector then leads to an electrical output signal, the frequency of which is equal to the frequency difference between the two incident light beams. This frequency difference is equivalent to the Doppler frequency shift.

A geometrical representation of the instrument is shown in Figure 1. It is noted from this figure that the three scatter beams are collected at 120° intervals around the LO beam and at an angle, α , with the LO beam. The angular relations between the Doppler frequency shifts and the velocity components for the arrangement in Figure 1, are given in Table I. It is

important for any given flow measurement, that this angular arrangement of the LDV instrument and laser beam be optimized in order to achieve the best accuracy in the velocity components being measured.

Physically the instrument consists of four heavy metal tubes in which the optical components are rigidly held (see Figures 3 and 4). Three of these tubes, referred to as the scatter tubes, contain the optics necessary for gathering the scattered light and directing it to a photomultiplier tube. The fourth tube, referred to as the LO tube, contains the optics required for collecting the LO beam, splitting it into three segments, and directing the segments to each of the three scatter tubes. The physical design of the instrument allows for convenient positioning of the optical components through external adjustments. The design also provides for adjustment of the scattering angle (α , in Figure 2) to 8.5° , 12° , 18° , and 28° * with the use of various spacers between the scatter and LO tubes.

The various optical components located in the scatter and LO tubes are shown in Figure 2 , which is an optical schematic of one "leg" (scatter and LO tubes) of the three-dimensional instrument. This "leg" is typical of all three "legs" of the instrument.

The components and adjustments of each scatter tube were designed to provide for collection of light from a very small field of view. The intersection of this field of view with the focused LO beam at a point in a flow field defines a region called the scattering volume, from which the Doppler frequency shifted light is received. The size of the field of view and therefore the scattering volume, can be adjusted with the variable front aperture and field stops provided in each scatter tube. The front aperture is continuously

*The scattering angle remained at 8.5° for all tests reported during this program.

variable from closed to 15.0 millimeters diameter, and the field stop is variable in fixed diameters of 25, 100, 200, 400, 600 and 1000 microns. The smallest field of view is defined with the front aperture at 15.0 mm and the field stop at 25 μ .

In each scatter tube, the first lens (L1 in Figure 2) receives the light from the scattering volume and collimates it. The collimated light is then reflected off four mirrored surfaces, the purpose of which is to match the scatter beam and LO path lengths as described in Section 2.5.2. The light is then focused by lens, L2, onto the field stop (FS1) which blocks light that does not originate within the focal volume. Following the field stop, lens L4 collects the light which passes through the stop and focuses it onto the photocathode of the photomultiplier tube through a beam splitter which is used to align it with the segment of LO light from the LO tube.

In the LO tube, the LO light beam is first received by a doublet, L8 and L6, which collect and collimate it. The collimated light then passes through an acousto-optical modulator which imparts a frequency shift of either 19 or 57 MHz (See Section 2.3 for further discussion of the modulator). After leaving the modulator, the light passes through a rotatable polarizer which is used to reduce the intensity of the LO light. The light then strikes a tetrahedral prism which splits the beam into three segments. Each segment passes through a focused lens, L5, the beam splitter, BS1, through which the scatter light is passing. The LO beam is then aligned with the scatter beam at the focus on the PM tube.

Various refractor plates, RP1, RP2, and RP3 are located within the instrument to provide for alignment of the scatter and LO beams. RP1 provides for positioning of the scatter beam so that it will pass through the field stop; RP2 provides for positioning of the LO beam on the beam splitter, BS1; and RP3 provides for positioning of the LO beam on the beam splitting tetrahedral prism.

With the instrument properly aligned, each of the three scatter tubes will receive Doppler shifted light from a region called the scattering volume. This volume is defined by the intersection of the scatter tubes' focal volume with the LO beam which is also focused. The scattering volume for the LDV system is the equivalent of the physical probe of conventional measurement systems. In order to provide for movement of the scattering volume within a flow field, the instrument and laser are mounted on either side of the LDV mounting stand seen in Figures 3 and 4. Cross blocks with graduated dials in 0.001 inch provide for movements of the LDV instrument and laser in three directions. Such movements allow for velocity measurements within a flow field volume of approximately one cubic foot.

During measurement programs with the LDV instrument, it was found that the instrument performed well whenever it was properly aligned. Such a proper alignment proved to be difficult to achieve in the early measurement programs. This difficulty was largely attributed to improper bore alignment. The bore alignment refers to the alignment of the LO beam so that the center of the beam and the center line of the LO tube coincide along the entire length of the tube. Once the proper bore alignment was achieved, the instrument was relatively easy to use. In latter measurement programs, the instrument alignment was achieved routinely with little difficulty.

2.2 LASER EQUIPMENT

The objective of this section is to discuss the characteristics of the laser light, produced by the laser light equipment, which are important to the LDV system. First, the laser equipment used during this program will be described, then the characteristics of the laser light, which are significant to the LDV system, will be discussed.

The two types of laser equipment which were used during this program were a Raytheon Model LG 12 and a Coherent Radiation Laboratories Model 53, both of which were continuous wave argon gas lasers. The Raytheon

laser was used throughout the major portion of this program while the CRL laser was only in use during the latter portion.

The Raytheon LG 12 was rated at 1 watt, TEM₀₀, with an output beam diameter of 2.2 mm at the $1/e^2$ points. This laser had no provisions for selecting single line outputs; therefore, the output consisted of several lines, the strongest of which were at 4880 Å and 5145 Å. Optical filters were used in the LDV system to select only the 4880 Å line which had the highest relative power for use in LDV heterodyning.

The CRL Model 53 was rated at 6 watts, TEM₀₀, with an output beam diameter of 1.5 mm at the $1/e^2$ points. This laser incorporated a prism which allowed for selection of various output lines. In the LDV heterodyning experiments, the prism was used to select the 5145 Å line which had a power output of 2.5 watts.

The most important characteristics of the laser light in the LDV system were the power or intensity, the coherence, and the axial mode spacing. The intensity of the laser light is important because of the relation between the scatter intensity, the incident intensity, and the particle concentration. For a given particle concentration within a flow field, the intensity of scattered light will depend on the intensity of the incident light. Since it is the scattered light which has the Doppler frequency shift, and therefore the velocity information, it is desirable to receive as much scattered intensity as possible. Such a strong scatter intensity provides better S/N at the photomultiplier output. A strong incident laser light also allows for making LDV measurements at reduced tracer particle concentrations which is desirable since a reduction in tracer concentrations also reduces the requirements on the tracer system. The practical point made here is that much more flexible operation of the LDV system is obtained with an increase in laser intensity. This point was demonstrated when the increased power provided by the CRL laser equipment was used in making LDV measurements.

The next characteristic of the laser light which is important is the coherence. As shown in Reference 7 and discussed further in Section 2.5.2 of this report, a lack of coherence in heterodyning experiments results in significant loss in the efficiency of the heterodyning process. Section 2.5.2 describes two methods for maintaining the laser coherence for heterodyning experiments. One method is to constrict the path lengths of the scattered and unscattered or LO beams to be equal. The other method is to place a Fabry-Perot etalon within the laser cavity. The etalon, when accurately aligned with the laser cavity mirrors, acts as a very narrow filter so that the output laser light has a higher degree of coherence than without the etalon. Both of these methods for maintaining coherence were investigated during the course of this work. The use of an etalon within the cavity of the Raytheon LG 12 laser proved operationally unsatisfactory due to the critical alignment between the etalon and the laser cavity mirrors which must be maintained in order to achieve a higher degree of coherence. It was found that such alignment could only be maintained for time periods of 2-3 minutes. The equalization of the scatter and LO light beam paths was found to be the most positive method of maintaining coherence in the LDV system.

The final characteristic of the laser light to be discussed is the axial mode spacing. In optical heterodyning with laser light in which the axial modes are a prominent part of the laser light bandwidth, signals at the PM tube output will appear at frequencies determined by the axial intermode spacing of the laser light. For the Raytheon LG 12 laser, the intermode spacing is 135 MHz and for the CRL Model 53, the spacing is 103 MHz. Therefore, depending on the laser used, signals at frequencies of either 135 MHz or 103 MHz will be present on the output frequency spectrum. The existence of these signals on the output spectrum makes the use of the frequency tracking units (Section 2.3) very difficult, since these units are not able to distinguish between the Doppler signal and the one caused by the mode heterodyning. Two methods of alleviating this problem are possible. The first method would be to insert

a narrow band frequency filter centered at either 135 MHz or 103 MHz, into the PM tube output, thereby blocking the mode produced signal from entering the frequency tracking units. Unfortunately, this filter would also block any Doppler frequencies which occur at the mode produced frequency. The other method would be to incorporate a Fabry-Perot etalon in the laser cavity. If properly aligned, the etalon will act to reduce or eliminate the laser modes; however, as noted in the previous coherence discussion, the alignment of the etalon in the Raytheon LG 12 laser has not proven satisfactory. Alignment of an etalon with the CRL laser was not attempted during this program; therefore, the use of an etalon for improving coherence and eliminating mode produced signals should be investigated in future test programs.

2.3 ASSOCIATED OPTICS

The Associated Optics of the LDV system are the optical elements that are not physically a part of the LDV instrument. These elements include a beam expander, mirror, and focusing lens; which expand, direct, and focus the LO beam, and an optical modulator which shifts the frequency of the LO beam.

The beam expander, mirror, and focusing lens are located in front of the laser as shown in Figure 5. The LO beam from the laser is directed into the beam expander which expands the beam diameter by a factor of 3.0. After passing through the beam expander, the beam is reflected off a front surface mirror mounted to reflect the beam at approximately 90° . The mirror mount contains adjustments which are used to align the LO beam along the center line of the LO tube of the LDV instrument.

After reflection off the mirror, the LO beam passes through a lens which focuses the beam. This focusing is important because it is the intersection of this focal volume with the focal volume of the scatter tubes which defines the scattering volume, i. e., the region from which the Doppler frequency shifted light is received.

In order for the scattering volume to be as small as possible and provide a maximum amount of scattered light intensity from that volume, it is necessary that the LO beam be focused in such a manner that the maximum intensity occurs in the smallest focal diameter. As shown in Reference 1, such a criteria is met for a Gaussian intensity distribution, as output from the laser, when the lens diameter is approximately equal to the length corresponding to the $1/e^2$ point on the laser intensity distribution curve. In the optical design of the LDV system, the laser beam was small compared to the focusing lens; therefore, a beam expander was used to increase the beam diameter so that it more nearly met the optimum focusing criteria.

The acousto-optical modulator is the final element to be discussed here. Before a physical description of its operation is presented, the reasons which require that such a device be used in the LDV system will be presented.

A given Doppler frequency shift on scattered light received by the LDV instrument, can be either positive or negative depending on whether the particle movement causing the shift was in either of two directions 180° from each other. This positive or negative shift and therefore the velocity direction is lost at the photomultiplier tube which is a square law detector and does not differentiate between positive and negative Doppler shifted frequencies. This directional information, i. e., the positive and negative nature of the Doppler shifted signals, can be established by imparting a known frequency shift to the LO beam. The use of the LO frequency shift becomes clear by considering the following example. If a scattered signal with a negative Doppler shift of 10 MHz heterodynes with an LO beam with a 19.2 MHz negative frequency shift, the PM output frequency will be at 9.2 MHz whereas a positive Doppler shift of 10 MHz will appear as 29.2 MHz.

The device used with the LDV system which imparts the frequency shift to the LO beam is an acousto-optical modulator. It is designed to shift approximately one percent of the input light by either 19.2 MHz or 57.6 MHz and selectively output only the shifted light. Measurements of the unit which was

installed in the LO tube of the LDV instrument, showed that light which was not shifted in frequency was normally being output along with the frequency shifted light. When operating the LDV instrument with the modulator, the PM output spectrum would show not only the Doppler shifted signal but also signals resulting from the heterodyning of the modulator frequency shift with the non-shifted light. These "modulator" signals were very useful in the testing at the MSFC 7-Inch Wind Tunnel. The signals were used as known frequency markers on the spectrum traces (see Figure 6) to establish the frequency of the Doppler signal.

While the existence of these modulator frequencies were useful in the wind tunnel tests, the frequencies are expected to cause difficulty if the frequency tracking units (Section 2.4) are used with the modulator frequencies present. In such a case, the tracking units would be unable to distinguish between the Doppler signals and the modulator signals. Before the tracking units can be used with acousto-optical modulator in operation, adjustments or modifications on the modulator must be made in order to eliminate the non-shifted light which is causing the "modulator" signals.

2.4 ELECTRONIC SIGNAL PROCESSING EQUIPMENT

The electronic signal processing equipment is considered to consist of the electronic instrumentation required to analyze the Doppler signal from the photomultiplier tube to the point that significant velocity data may be obtained. During the course of the work on this program, it became evident that two systems for processing the Doppler signals would be advantageous. One system would be capable of detecting low level Doppler signals and would only provide information from which the mean flow velocity could be obtained. The other system would provide both mean velocity and turbulent flow information but would require signal-to-noise ratios of 13 db or better.

The following segments discuss the characteristics and operation of the two signal processing systems.

Spectrum Analyzer System

The spectrum analyzer system for processing a Doppler signal was established in order that mean velocity data could be obtained in flows in which the Doppler signal level was low. As seen in Figure 30, this system consists of three spectrum analyzers, three amplifiers, a pulse generator, a signal analyzer, and an X - Y recorder.

In this system, the three Doppler frequencies are initially processed by the three spectrum analyzers. The vertical output of each of the spectrum analyzers is in turn processed by a signal analyzer (Hewlett-Packard Model 5480) and stored in its magnetic core. The signal analyzer provides an improvement in S/N level over that displayed by the spectrum analyzers. This improvement is a function of the number of sweeps or signal samples which it processes for a given test time. The maximum rate at which the signal analyzer could process the signal spectrum was at 100 sweeps/sec which corresponds to a sweep rate of 1.0 millise/c/cm. In order to provide the signal analyzer with the maximum number of sweep/sec from the spectrum analyzer it was necessary to increase the spectrum analyzer sweep rate from 3.0 millise/c/cm to 1.0 millise/c/cm. The electric modifications needed to increase the spectrum analyzer sweep rates are given in Reference 8. External synchronization of the spectrum analyzers and signal analyzers which is accomplished with the pulse generator, ensure that the signal analyzer achieve the maximum signal availability.

In order to make velocity measurements with this system, the three Doppler frequency spectrums obtained during a test are processed and stored in the magnetic core storage of the signal analyzer. When the test is complete, the stored signal spectrums are recorded from the magnetic core storage using an X - Y recorder. Comparisons of the noise and Doppler signal spectrums are then made in order to identify the Doppler signal. The frequency of the Doppler signal is established with the use of marker frequencies which are produced by the acousto-optical modulator (Section 2.3).

This system can also be used with a tape deck to record the vertical output from the spectrum analyzers. Such a recording of the spectrum output allows for multiple analysis of the Doppler signal within the signal analyzer, since the Doppler spectrums are recorded and can be repeatedly processed. The use of the tape system is desirable when the S/N level is very small and the test time is short.

During the test program conducted at the MSFC 7-Inch Wind Tunnel, this system was shown to be very effective in the acquisition and identification of low-level Doppler signals. Three typical Doppler signals obtained with this system during the wind tunnel tests are shown in Figure 31.

Frequency Tracker System

The frequency tracker system incorporates an instrument which "locks onto" and "tracks" the Doppler signal. This instrument (Frequency Tracker) provides as outputs a mean voltage level corresponding to the mean Doppler frequency or flow velocity and a fluctuating voltage level (AC) corresponding to the Doppler FM fluctuations or flow turbulence. In order to provide a clearer understanding of how this system operates the relationship between the mean and turbulent flow parameters and the Doppler frequency shift parameters will be presented. A more comprehensive discussion of this relationship is given in Reference 5.

The normal notation of the theory of a turbulent flow assumes that the flow can be divided into temporal mean and turbulent parts. The velocity component in the X direction is then written as

$$U(t) = \overline{U(t)} + U'(t) \quad (1)$$

where $\overline{U(t)}$ = mean velocity.

$U'(t)$ = turbulent velocity fluctuation.

Similar expressions can be written for the Y and Z directions; however, for simplicity only one component will be discussed here.

Considering Equation 1, and comparing the components there with the Doppler frequency shifts, the following relations can be defined;

$\overline{U(t)}$ corresponds to carrier frequency ($f_c(t)$)

$U'(t)$ corresponds to frequency deviation ($f_{dev}(t)$)

Then an expression of the instantaneous Doppler frequency shift may be written as

$$f(t) = f_c(t) + f_{dev}(t) \quad (2)$$

which represents the Doppler frequency shift relation corresponding to the velocity relations (Equation 1).

Further definition of a turbulent flow is made by defining the frequency with which the observed velocity fluctuations occur. This frequency is called the signal frequency (f_s) and is used in defining both the turbulence energy spectrum and the scale of turbulence. The relationship between the signal frequency, the carrier frequency, and the frequency deviations for the Doppler signal is illustrated in Figure 6.

It might be noted in Figure 6, that the carrier frequency is shown not as a signal frequency but as a continuum of frequencies due to instrument broadening. This broadening of the Doppler frequency shift is caused by the velocity gradient across the finite scattering volume and by the finite aperture of the scatter tubes which allows the instrument to collect light over a range of frequencies (since the Doppler shift depends upon scattering angle).

The effects of the instrument broadening on the operation of the frequency tracker and on the analysis of the data can theoretically be shown to be significant for high velocities and small scattering angles (Reference 1). In the flow measurements made to date with the tracking system, the effects of instrument broadening was neglected due to time limitations and the pre-dominance of other problems.

The frequency tracker incorporates a frequency discriminator as the main component within its "tracking" loop. The discriminator gives an instantaneous voltage output proportional to the instantaneous frequency of the voltage applied to its terminals. The amplitude of the output may be expressed as composed of two components, one component is a mean amplitude directly proportional to the mean frequency f_c and therefore to the mean velocity $\bar{U}$. The other component is a fluctuating amplitude component f_{dev} , proportional to U' . Also the frequency deviation, f_{dev} , has a wave form associated with it which is the signal frequency f_s discussed earlier.

A schematic diagram of the frequency tracker showing the frequency discriminator in the tracking loop network is shown in Figure 7. When the network is "locked", a Doppler signal is mixed with a signal from the voltage controlled oscillator (VCO) to produce a difference frequency known as the intermediate frequency (IF) signal. The design of the network is such that the IF signal is maintained at 30 MHz. Any frequency deviation or modulation of the IF signal is then passed through the IF amplifier and band-pass filter. A limiter/discriminator then demodulates the signal so that the resulting output voltage is proportional to any deviation of the signal frequency from the IF. The output voltage is then amplified and used to drive the VCO so the instantaneous difference frequency between the Doppler signal and the VCO output frequency is reduced in the mixer and maintained at 30 MHz.

A DC and an AC output which are derived at the input to the VCO are provided for signal readout. The DC output voltage is proportional to the carrier frequency, f_c , and the AC voltage is proportional in magnitude to the frequency deviation, f_{dev} , and equal in frequency to the signal frequency f_s .

The tracker system is designed to operate over a carrier frequency range of from 5 to 50 MHz, but it may also be operated from 50 to 200 MHz at reduced performance. For any carrier frequency out to 50 MHz, the deviation

frequency can vary from 0 to 50% of that carrier frequency and the signal frequency can be from 0 to 50 KHz. The operating specifications out to 200 MHz are not presently known.

The sensitivity of the tracker is given as follows:

<u>Voltage</u>	<u>Sensitivity (Volts/MHz)</u>	<u>Range</u>
DC	0.1	0-50MHz
DC	0.025	50-200MHz
AC	0.1	0-50MHz
AC	Unknown	Unknown

The tracking accuracy can be maintained within $\pm (100 \text{ KHz} + 3\% \text{ of the deviation frequency})$ for the AC output.

The tracker that was available during this program was used in making one dimensional free jet turbulence measurement described in Section 4.2. Figure shows how the tracker was used during the tests. The AC voltage was read directly on an RMS voltmeter and also recorded on magnetic tape for computer analysis of the spectral distribution of the signal frequency, f_s . The RMS voltage which was proportional to the frequency deviation, f_{dev} , was used to define the turbulent intensity through the following relation

$$\text{Turbulent Intensity} = \frac{\sqrt{U'^2}}{U} = \frac{\sqrt{f_{\text{dev}}^2}}{f_c}$$

The mean flow velocity was obtained from a reading of the DC voltage which was proportional, through the tracker calibration curve, to the carrier frequency.

2.5 SYSTEM MEASUREMENTS

As a consequence of the development of the LDV system, several areas of investigation were defined due to problems in these areas or to the lack of definition of operational parameters in these areas. These investigations were conducted through measurement or testing programs within the defined areas. Those areas investigated were; the scattering volume, path length equalization,

electro-optical considerations, and the frequency tracker. In this section, the investigations within these areas are discussed with the aims of presenting the reasons for conducting the investigations and the conclusions resulting from the investigations.

2.5.1 The Scattering Volume

One of the main attributes of the LDV system is found in the fact that the system can perform flow field measurements without the need of physical probes within the flow. This system is designed to obtain flow measurements through optically receiving light for a region within a flow field called the scattering volume. Here, the scattering volume size is the equivalent of the physical probe size in conventional measurement systems. Whether the probe is a physical probe or an optical probe, it is necessary to have a knowledge of the probe size in order that limitations on the flow measurements due to the finite size of the probe can be defined.

Theoretical considerations for flow measurement require that the probe size be much smaller than the smallest flow perturbation which is to be measured. This would require an infinitely small probe which, in practice cannot be realized. Instead, the smallest physical probes (hot wire, pitot tube) generally are no smaller than 1.0 mm for the largest probe dimension.

Although the LDV system was designed to be capable of achieving measurements with high spatial resolution, i. e., small scattering volume, it remained to be shown that in truth the system had this resolution. For this reason tests were conducted to measure the scattering volume size.

Before discussing these tests and presenting the results, some further definition of the scattering volume should be made. As seen in Figure 8, the scattering volume is defined as the intersection of two focal cylinders, one formed by the lens which focuses the laser beam and the other formed by the scatter tube optics. The theoretical considerations given in Reference 1 and 6 show that this intersection can be considered as the intersection of two cylinders with dimensions as shown in Figure 8. Reference 1 and 6 further

show that assuming defraction limited optics, the smallest scattering volume that can theoretically be achieved with the LDV system (scatter angle, $\alpha = 8.5^\circ$) will have a maximum dimension of approximately 1.0 mm and a minimum dimension of 0.03 mm (Figure 8).

With these dimensions in mind, it was left to show how well the theoretically predicted dimensions compare to actual measured values. The experimental technique which was used consisted of the movement of a small free jet (1.1 mm dia.) along the maximum dimension of the scattering volume (Figure 9) and observing the relative amplitude change of the signal spectra displayed on a spectrum analyzer. Using this technique, measurements of the signal change for jet movement through the scattering volume was made for each of the three tubes. These measurements were conducted with a range of field stop and apperture settings to determine the setting that defined the smallest scatter volume length. Figure 9 shows the measurements of the minimum length obtained along with the apperture and field stop setting at which the measurements were made. Noting that a possible inaccuracy of approximately ± 0.2 mm exists in the measured scattering volume length due to a lack of definition of the jet width, the curves of Figure 9 show that the maximum signal "seen" by each tube fall within a length of 1.0 mm. This value is seen to be consistent with the theoretical definitions and also with conventional probe sizes (i. e. hot wire and pitot tubes).

The scattering volume measurements also showed that all three scatter tubes could be adjusted to define the same scattering volume length at the same point in space.

Due to the relatively large size of the jet in comparison with the expected small dimension of the scattering volume, no attempts were made to measure it.

The conclusions made for these measurements were that the largest dimension of the LDV scattering volume was consistent with conventional

probe sizes and that all three scatter tubes could define the same scattering volume in space.

2.5.2 Path Length Equalization

The term "path length equalization" as applied to the LDV system refers to the equalization of the paths followed by the main or local oscillator (LO) beam and that followed by the scattered Doppler shifted light beam. The discussion here is concerned with the reasons that these paths should be equal and the technique used for making the paths equal.

The basis for requiring that the path lengths be equal stems from the loss of heterodyne efficiency resulting from a loss of coherence. Without going deeply into a discussion of coherence (see Reference 5 for detailed discussion) the following definitions will be made.

The laser light is a light source of narrow but finite spectral bandwidth. A coherence time, which is the inverse of this finite bandwidth, is defined such that for time intervals short with respect to it, the laser can be considered to be a monochromatic source. When multiplied by the velocity of light, the coherence time becomes a coherence length.

Forman in Reference 1 shows through theoretical considerations, that the heterodyne efficiency for two beams from the same source will show a decrease depending on the number of axial modes excited, or spectral width, as the path length difference between the two beams approaches the coherence length of the source.

For the Raytheon LG 12 argon gas laser used throughout all but the latter part of this program, the coherence length is approximately 10 cm. Consequently, the difference between the scattered and LO light should have been small in comparison to 10 cm. in order to have efficient heterodyning. However, it was found that for the instrument at the 8.5° scattering angle, the path length difference was approximately 20.0 cm. As a result of this mismatch, the signal strength was noted to be poor.

Throughout most of the one dimensional measurements, provisions for equalizing the path lengths using accessory optics were required. During the latter phases of this program, modifications to the LDV instrument were incorporated to make the path lengths for all three tubes equal. This modification, which is shown schematically in Figure 2, allows for manual adjustment to increase the scatter beam path length up to 35 cm, and has provisions for larger adjustments if required by use of the instrument with larger scattering angles.

Another technique for keeping the heterodyning efficiency high, is to use a laser source of single frequency or single mode (i. e., one with very small spectral width). Such lasers have very long coherence lengths, thus a moderate path length mismatch would be small in comparison. A method of reducing the spectral width of a laser source is available in the Fabry-Perot etalon. The etalon when placed within the laser cavity between the Brewster window and end mirror and properly aligned with the laser cavity mirrors, acts as a very narrow filter to effectively reduce the laser spectral width. However, attempts at using such an etalon within the LG 12 laser cavity were unsatisfactory. It was found that the positioning of the etalon was so critical in order to achieve the desired filtering, that thermal drift within the cavity made it necessary to almost constantly adjust the etalon. Such adjustments were considered to be operationally unsatisfactory and therefore the use of the etalon was abandoned.

The measurements concerned with the equalization of path lengths indicated that for the LDV system being discussed, the most positive assurance of optimum heterodyning is best achieved through physically adjusting the path lengths of the scatter and LO beams to be equal.

2.5.3 Electro-Optical Considerations

The electro-optical considerations for the LDV system encompass the photomultiplier tubes and the optical components which direct the light on the PM tubes. As a part of the development of the LDV system, it was found that

a more precise definition of the operational parameters of the photomultiplier tubes and optical components was required to optimize the system. Many tests and measurements were made to define these parameters. Only the most significant results are mentioned here.

The photomultiplier tube used in the LDV system is an RCA 8645. This device was selected because its characteristics conformed to the LDV design criteria discussed in Reference 5. As installed in the LDV system, the PM tube has connectors for the PM tube operating voltage input (800 - 1800 volts), for the Doppler signal output, and for a voltage reading which is proportional to the anode current being drawn by the tube.

From an operational standpoint, it is important that the PM tube operate below its saturation point. This saturation occurred when the anode voltage was 12.5 millivolts which corresponded to an anode tube current of 0.5 milliamps. It was determined that operation of the tube either at or near saturation resulted in an unstable output signal spectra. Best operation was found to occur at approximately 6 - 7 millivolts.

As shown in Reference 5, the operational criteria for making the signal-to-noise ratio from the PM tube as large as possible is that the local oscillator power (P_{LO}) be at least 5 times greater than the scattered light power (P_s) as long as the PM tube is operated below saturation. Since it was found that the amount of P_{LO} available was always greater than P_s and was always capable of saturating the PM tube for any operating voltage, measurements of the minimum scatter power at which sufficient S/N (15 db) could be achieved was considered an important parameter. This minimum scatter power was found to be approximately 1.0×10^{-9} watts. Thus, if scattered powers at this value or greater can be achieved for any particular system arrangement (i. e., incident laser light power, particle concentration, and scatter tube aperture setting) then a sufficient S/N level might be expected. However, this does not mean that a good signal is guaranteed since the scattered light must be properly aligned with the LO light in order to achieve the desired

signal/noise. The alignment of the two beams for each tube and the instrument itself was perhaps the major difficulty in achieving sufficient S/N, since in almost all cases (except where there were insufficient tracer particles) the scattered light needed could be achieved either by increasing the incident laser power or increasing the scatter tube field stops. It should be noted here that although increasing the scatter tube field stops increases the amount of scattered light received, it also increases the scattering volume (see Section 2.5.1).

As noted in the previous paragraph, the optical alignment difficulties were perhaps the major difficulty in achieving sufficient S/N levels, assuming that the scatter power was greater than 1.0×10^{-9} watts. These difficulties will not be discussed here due to the length that such a discussion would require. It was found that all such difficulties could be overcome once an intimate knowledge of the instrument was obtained.

2.5.4 Frequency Tracker

The frequency tracker as described in Section 2.4 is shown to be an integral part of the LDV system. This instrument is designed to effectively demodulate the Doppler signal to voltage components from which the velocity data can be obtained. The operation of the instrument is such that when the instrument is "locked" onto the Doppler signal, a DC voltage corresponding to the mean flow velocity and an AC voltage corresponding to the flow turbulence are read as the outputs.

The problems with the tracker which caused the most concern were an inconsistency in its tracking or locking capability and an imprecise definition of its accuracy.

The inconsistency in the tracking or locking capability was attributed primarily to the lack of sufficient S/N levels. The specified S/N level for proper tracking was 13 - 15 db; however, during the early development stages such signal levels were difficult to achieve. Since then, improvements in the LDV system allow S/N levels as high as 30 - 35 db to be obtained. As a result of

the improved S/N levels, future problems with locking and tracking are not expected to be encountered.

Measurements of the AC noise levels and the accuracy with which the DC level can be read were made. It was found that the tracker AC noise level was normally 10.0 mv RMS. When making a turbulence measurement with the tracker, the data analysis should allow corrections for this noise level. The DC accuracy measurements showed that the DC voltage output could be read to within 1.0 mv or approximately 1.0 ft/sec.

Further, more precise measurements of the tracker accuracy are being conducted by the manufacturer (Raytheon Company). These measurements are to help in defining improvements which will be incorporated into two new trackers being built. It is expected that any major improvements will be incorporated into the old tracker which was used for this program.

3.0 TRACER SYSTEMS

In the truest sense, the LDV system only measures the movement of the small tracer particles within a gas flow, so in order for the particle information to be an accurate representation of the gas flow, careful consideration must be given to the characteristics of the tracer particles within the gas flow. It is this consideration that led to the investigation of tracer particles for the LDV system. Initial investigations indicated that the problems of providing a suitable tracer particle in the concentrations necessary for the LDV system would be very difficult to solve. This section explores these problems through discussions of the two phase flow considerations, tracer particles and injection techniques, and techniques for measuring particle size and concentration.

3.1 TWO-PHASE FLOW CONSIDERATIONS

As discussed here, a two phase flow is a gaseous flow in which liquid or solid particles are entrained. The primary two-phase flow consideration, from the standpoint of the LDV system, is a definition of the particle characteristics that are required in various flow fields, in order that the particle movements accurately represent the movement of the gas flow. Such a definition can be made from the results of a theoretical two-phase flow model which represents typical flow field conditions. This theoretical investigation was conducted by Berman and presented in Reference 2. The discussion here is primarily a summary of Berman's work.

Berman's theoretical approaches to the analysis of the particle-fluid interactions were for special cases in which solutions to the defining particle-fluid equations could be obtained. In one of these approaches, the equations of motion were solved for the case of a single particle in a turbulent field. This case was the most generalized and allowed the analysis of particle-fluid motion for various turbulent frequency spectrums, with the following assumptions imposed:

1. The particle is small and spherical so that a simple expression can be used for the drag coefficient based on the relative motion.
2. The particle is small compared to the smallest wavelength of turbulence.
3. The flow field is not perturbed by the presence of the particle.
4. The fluid and solid particle paths coincide.
5. The turbulence is homogeneous and steady.
6. The turbulence is not effected by solid boundaries.
7. Several assumptions relating to the nonlinear terms in the motion equation are also made.

Berman applies the particle fluid equations, which result when the above assumptions are imposed, to the case of turbulence in a free-jet and in pipe-flow. His results indicate that for a particle size of 1.0 micron or smaller, with a density of 1.0 gm/cm^3 , the error in the mean squared velocity relative to the mean squared fluid velocity will be 2% for spectral frequencies up to 20 KHz and Mach numbers up to 2.0. This error is shown to be even smaller for lower particle mass densities and particle size.

Although Berman's analysis is not exact due to the assumptions imposed in arriving at solutions, it does provide a basic definition of the desired particle characteristics, i. e., 1.0 micron or less in diameter and have a low mass density. A further characteristic inferred for the analysis is that the particles be spherical. This cannot be considered as a absolute characteristic since non-spherical particles can be treated as spherical particles, in a two-phase flow analysis. However, such treatment would further complicate the particle-fluid analysis. For the purposes of the particle investigations discussed in the next section, a spherical or nearly spherical particle will be considered a desired characteristic. Since Berman's analysis was only concerned with the motion of a single particle in a turbulent field, future theoretical two-phase flow investigations should be concerned with defining the effects of particle-particle collisions assuming typical particle size distributions and concentrations which are expected in actual LDV operation.

3.2 TRACER PARTICLES AND INJECTION TECHNIQUES

In the investigations of tracer systems for the LDV system, it was found that a particular tracer particle could usually only be injected into a gas flow by a particular technique. For this reason, each type of particle will be described along with the injection technique used for it. Before describing the various tracers and injection techniques which have been investigated, a clearer definition of the requirements or desired characteristics for a tracer particle and for an injection technique will be made.

In order to choose a satisfactory tracer material, consideration must be given to the requirements of the LDV system, the gas flow, and the test facility. One of the requirements imposed by the LDV system stems from the design criteria that the system operate with light scattered in the Mie regime. Scattered light in the Mie regime requires that the particle size be on the order of the wavelength of the incident light, which for the laser light used with the LDV system, means that the particle size should be approximately 0.5 microns. The only requirement on a tracer injection technique is that the particle concentration (in particles/cm³) at the submicron size, provide scatter intensities, with the incident laser powers being used, which are sufficient to obtain a useful Doppler signal level.

A requirement of the gas flow is that the particles accurately follow the flow fluctuations. As discussed in Section 3.1, this requires spherical or nearly spherical particles with diameters of 1.0 micron or less and with mass densities as low as possible. Table II compares the diameters, mass densities and other characteristics of most of the materials that were investigated during the course of this work.

In general, the requirements for compatibility with the test facility are that the tracer be non-toxic, non-corrosive and non-abrasive, and not create an explosive hazard. These requirements will vary with the type test and test facility at which measurements are being conducted. A tracer may be toxic, corrosive, abrasive, and explosive to some degree and still be

permitted for a particular test if proper preparations and precautions are taken to minimize these undesirable characteristics.

The only requirement on the injection technique is that it be capable of providing the particle concentrations (in particles/cm³) which, for incident laser powers used with the LDV system, will provide scatter intensities sufficient to obtain a useful Doppler signal level. There are two approaches for achieving this requirement. One is to inject the particles in-line while the flow facility is operating and the other is to inject the particles into an air-supply chamber prior to operation of a facility. Investigations of these two approaches have shown both advantages and disadvantages. The approach for injecting the particles during a flow facility operation allows for the injection of particles at pressures which are lower than before the facility is operated; however, the particles must be injected at high rates, especially in large flow rate facilities such as wind tunnels. On the other hand, the approach for injecting into supply chambers prior to running can be accomplished at relatively low flow rates; however, such supply chambers may be at high pressures, thus requiring the particles be injected at high pressures.

During the investigation of the tracer particles and the injection techniques, it was found that the tracer systems met the desired requirements in varying degrees. In the remaining paragraphs, the tracer systems which were investigated are discussed with the aim of providing an indication of the degree with which each met the desired requirements.

Smoke Bomb System

The first tracer system which was tested (Figure 10) consisted of a chamber in which smoke was mixed with air and passed into a plenum chamber and out of a free jet nozzle. Smoke bombs manufactured by Superior Signal Company, Spotswood, New Jersey, produced the tracer particles which were zinc chloride in union with atmospheric moisture.

This technique was used not only for free jet measurements but also for some early measurements at a MSFC wind tunnel facility. Both of these

uses only required that the system operate at pressures slightly above atmospheric. Operation of the system at pressure much above atmospheric was never attempted.

Using a Stokes experiment, a mean mass particle size of 2.15 microns was found to be produced by the smoke bomb. Photomicrographs of the particles collected in the Stokes experiment indicated that particles in the range of 0.2 to 5.25 microns were present. Particle counts from the photomicrographs gave a mean mass particle size of 2.3 microns which compared well with the size determined with the Stokes experiment.

The smoke concentrations produced, were found to be sufficient to provide signal-to-noise ratios of 20 db and better on free jet measurements with an incident laser power of 0.3 to 0.5 watts. Due to an inconsistency in the burning rates of the smoke bombs, it was found to be very difficult to maintain or repeat particle concentrations. The variations in the burning rate produced variations in the Doppler signal and made optical adjustments to optimize the signal strength very difficult.

An undesirable aspect of the smoke bomb technique was the corrosive nature of the residue which collected inside the flow channels in which it was used. If the residue was not removed shortly after it collected, damage to the flow facility resulted.

Fluidized Bed Technique

The next investigation in injection techniques was concerned with the introduction of solid particulate materials into gas flows through the use of a fluidized bed. The fluidized bed technique as seen in Figure 11, would suspend the particles in the air by passing the air through the bed of materials. The rate at which the air was passed through the bed of particles determined the quantity of particles entrained in the air flow. Some degree of regulation on the concentration could be obtained by adjusting the ratio of the by-pass air flow to the air-flow through the bed.

Measurements to determine the operational characteristics of this system indicated that the flow velocity through the bed should be maintained at a value less than 1.0 ft/sec. At higher velocities, the fluidized bed began to slug resulting in fluctuations in both concentration and flow velocity.

The use of this technique was limited to free jet measurements during this program; however, the technique contained distinct possibilities for injection of particles at high rates and at high gas pressures. This was evidenced by the simplicity of the system and by the ease with which concentrations could be achieved.

Of the many materials investigated and tested in the fluidized system, (see Table II), the polyvinyl chloride materials, trade name Geon, were found to offer the most desirable tracer characteristics. Examinations of the Geon 126 material with an electron microscope (Figure 12) showed that the material was made up of almost spherical particles with diameters of approximately 0.3 microns. This information along with its non-corrosive, non-toxic, and non-explosive nature, its low specific gravity, and low cost indicated that this material met most of the tracer requirements. However, problems with agglomeration due to static changes and with design of a more controllable technique for injecting the particles led to further investigations of other materials and techniques.

Chemically Reactive Gas-Mixing

A disadvantage of the fluidized bed technique was that the entire flow had to pass through the fluidized bed to obtain high particle concentration. To avoid this restriction and permit easier addition of a tracer system to existing facilities, another particle injection technique was developed. It consisted of the mixing of hydrogen chloride and ammonia gases to produce ammonium chloride particles within air flows. A sketch of such a system which was used on some free jet mean velocity measurements is shown in Figure 13. This system is composed of two gas regulation and measurement networks, one for each of the two gases to be mixed. The gases were normally mixed in a ratio

by weight of 35% NH_3 and 65% HCL , the flow rates being determined by the required concentration level for an assumed particle size (usually 1.0 microns) and a given air flow rate.

Since this technique is a chemical one, the formation of the ammonium chloride particles first begins on a molecular scale and would remain on that scale if it were not for the agglomeration and crystalline growth of the particles. For this reason, the particle size and concentration produced will depend on the method by which the gases are mixed and dispersed and on the crystalline growth rate. The study of mixing and dispersing techniques for various flow conditions and the crystalline growth rate of the particles was not undertaken in this program due to the scope of such an investigation. Consequently, no specific information on the particle size and concentration produced by this technique were obtained.

The gas mixing program, was accomplished with two tubes which directed the ammonia and hydrogen chloride gas flows together in a plenum chamber in which the air flow was passing. This method of mixing the gases was used in some high speed free jet mean velocity measurements and in a test program at AEDC to measure the reverse flow in the base region of a clustered engine model. A lack of optimization in the mixing and dispersion of the particles in both of these tests was evident by the observed accumulation of tracer materials within the plenum chambers.

This technique of particle injection was chosen for each of these tests because of the comparative ease with which the technique can be applied to particle production in "high" pressure* plenum chambers with large ($> 1.0 \text{ lb/sec}$) flow rates.

Perhaps the weakest characteristics of this system are found in the corrosive and toxic nature of the gases which are used. Both gases require

*This technique is limited to "high" pressures which are below the bottle pressure of ammonia. At 70°F , ammonia bottle pressure is 114 psig.

special handling equipment and safety precautions in order to protect a facility and personnel. Even with these precautions, the use of this system at most facilities would be questionable due to the nature of these gases.

Shearing Jet Aerosol Generator

The final technique which has been investigated offers the most promising solution to the tracer problem. This technique produces liquid tracer particles, by forcing air at high speeds from jets immersed in a bed of the liquid. The high speed jets produce large shearing forces which break the liquid into small particles, which are then carried away from the liquid bed by the air flow. A sketch of this technique is shown in Figure 14.

A comprehensive study of this technique for aerosol production is presented in Reference 3. A commercially available aerosol generator (ROYCO Instrument Company, Menlo Park, California) which incorporated some of the techniques discussed in Reference 3, was obtained for testing and possible use with the LDV system. Initial tests with this generator demonstrated excellent operational characteristics with the LDV system. This generator used a dioctyl phthalate (DOP) liquid and was designed to produce a mean particle size of 0.3 microns. This generator was used to provide the tracers for a series of one-dimensional turbulence measurements in a free jet at subsonic velocities.

Since the ROYCO generator was not designed for large flow rates or high pressures, which were required for planned LDV measurements, investigations were conducted to establish design criteria for use in constructing larger, heavy duty generators. These investigations were conducted to determine the particle size and concentration produced with different liquids, nozzle configurations and operating pressures.

Measurements of the particle size and concentration produced under various operating conditions by the ROYCO generator were made with a jet impactor technique for particle sizing. The measurements are presented

in Figures 15 and 16. These figures compare the particle size and concentration produced with the nozzle configurations seen in Figure 17. The ROYCO generator was modified to allow for testing of different nozzle configurations. These configurations were operated in a DOP liquid and a silicon liquid (20 centistoke) under various nozzle pressure ratios.

The modified nozzle as seen in Figure 17 was evaluated because such a nozzle could be constructed easily and adapted to larger generators. The silicon liquid was evaluated because of the inert nature of the liquid in comparison with the DOP liquid which is a plastizer and can cause softening of many synthetic materials which might be found at many flow facilities. The silicon liquid was also found to have a lower toxicity level than the DOP liquid.

The aerosol data trends shown in Figures 15 and 16, indicate that higher operating pressures produce larger concentrations, smaller particle sizes, and a smaller percentage of large particles. The only exceptions to this trend is the combination of the modified nozzle with the silicon liquid. The DOP liquid produced smaller mean particle sizes and larger concentrations than the silicon liquid. It appears that the best operating pressure ratio to achieve the smallest mean particle size and largest concentration is at pressure ratios in the range from 3.0 to 4.0. The modified nozzle also provided better particle characteristics for the DOP liquid than the ROYCO nozzle; however, this was not true for the silicon liquid.

After examination of these measurements, it was concluded that a larger generator could be built to provide concentrations of up to 10^8 particles/cm³ with a mean mass particle size of approximately 1.0 microns. Such a generator was designed to have a flow rate of 1.0 lbm/sec at pressures up to 100 psig. The design also provided that the generator be constructed in two stages as seen in Figure 14, in order to provide more liquid surface area per jet.

After constructing and testing a generator according to the initial design specifications, several design flaws were noted. It was found that if

the air velocity became larger than 1.0 ft/sec, the generator would spew large droplets of the liquid. In order to keep the air velocity low for the desired 1.0 lbm/sec flow rate, it was necessary to increase the generator size from an original 1.0 foot in diameter to 2.0 feet in diameter. It was further found that the oil temperature should be kept between 50-80°F in order to keep the concentration optimized. For this reason, provisions in a revised generator design included a heater to keep the inlet air warm and reduce the cooling of the liquid bed by the expanding air. Baffle plates were also included in the revised design to help reduce losses due to splashing from the liquid bed. An air by-pass line was also included to allow for reductions in the concentration level.

A generator which incorporated these revised design specifications was constructed and installed at the MSFC 7-inch wind tunnel facility as shown in Figure 18. Measurements of the output from this generator with silicon liquid and a nozzle pressure ratio of 3.0 showed that the mean mass particle output was 1.08 microns with a concentration of 1.94×10^8 particles/cm³.

The only operational environment in which this technique for particle injection has not proven itself is in the injection or production of particles at high pressures inside the generator. Such a capability is desirable since many test facilities require that the particles be introduced into high pressure air supplies.

Although none of the tracer materials or injection techniques investigated have been found to meet all the desired requirements, each technique and material offers characteristics which are suitable for specific test programs and test facilities. One must evaluate the specific test and choose the material and technique accordingly.

In light of all the tracer investigations which have been conducted, it is felt that the most promising solution to the tracer problem at the present time is the generation of liquid particles with shearing jets.

3.3 TECHNIQUES FOR TRACER PARTICLE SIZE AND CONCENTRATION MEASUREMENTS

Since the LDV system measures the movement of particles within a gas flow, the accuracy with which the particle movements represent the movements of the gas flow is important in evaluation of the LDV measurements. As indicated in the discussion of two-phase flow considerations, the accuracy is primarily dependent on the size of the particle. So in order to assure that the particles are of sufficiently small size to accurately represent the gas flow, measurements of the particle size within the flow must be made. It is not only desirable to know the particle size, but also the concentration since the concentration is important in assuring that the number of particles within the scattering volume is sufficient to provide a continuous Doppler signal from which statistical velocity data can be obtained.

For these reasons, various techniques for making tracer particle size and concentration measurements were investigated. These techniques included microscope examinations, a particle settling experiment, light scattering and transmission measurements, and a particle impaction device.

Although it is considered desirable to make the particle size and concentration measurements at the point at which the LDV velocity measurement is made, investigations of the various techniques indicated that only the light transmission technique offered this capability for a wide range of flow conditions. The other techniques were limited to making measurements in flows in which reliable isokinetic sampling could be conducted. Isokinetic sampling is largely limited to low speed laminar flows in which probes 1/4 inch ID and larger can be used. As a result of these limitations, most of the particle measurements were made either prior to injecting the particles or under controlled flow conditions.

Microscope Examinations

Particle measurements on most of the solid tracer materials investigated were made prior to injecting them into the flow fields. Using both

optical and electron microscope, these measurements determined if the solid materials, which were to be injected, were composed of particles that were roughly spherical in shape and 1.0 micron and below in diameter. Most of the solid materials which were examined showed that the particles were non-spherical in shape and too large to follow gas flows well. The best solid tracer material investigated was Geon 126, an electromicrograph of which is seen in Figure 12.

An extended use of the microscopic technique is available when it is used to size and count tracer particles which have been collected on a filter paper by flowing an isokinetic sample of the particle-gas flow through the filter. By counting the various sizes of particles seen within typically representative areas of the filter paper, the size distribution of the particles present can be obtained. By weighing the amount of material collected during a known time interval and flow rate, the concentration can also be obtained.

Stokes Experiment

A Stokes particle settling experiment was used in determining the mean mass particle size produced by the 3-minute smoke bombs and by the mixing of ammonia and hydrogen chloride gases to produce ammonium chloride particles. The Stokes particle settling experiment is based on the fact that for small spheres (with Reynolds Numbers less than 1.0) the drag coefficient is inversely proportional to Reynolds Number. Using this fact, a relationship between the particle diameter and settling or terminal velocity, for particles suspended in still air, can be derived.

In this experiment, the particles are injected into a settling chamber and the rate of fall of the interface which forms when the particles reach terminal velocity, is measured. When the particles are of reasonably uniform diameter, the interface is sharp and distinct; however, some difficulty is encountered when the particle size distribution is large, since the interface is not so well defined.

HAYES INTERNATIONAL CORPORATION

This experimental technique was used to determine a mean mass particle size produced by the smoke bombs of 2.15 microns and a mean mass particle size produced by the mixing of ammonia and hydrogen chloride gases, of 1.2 microns. It should be noted that due to the nature of this experimental technique, the above particle sizes are only an indication of the particle size that can be produced. Such a size may vary considerably due to agglomeration and crystalline growth when the particles are introduced to LDV flow systems.

Light Scattering and Transmission Measurements

The use of a light scattering device to make continuous on-line measurements of the particle-gas flow was investigated, since such a device appeared to offer advantages over the other more tedious particle measuring techniques. These devices are sold commercially and usually referred to as particle monitors or particle counters. Upon discussing these devices with several persons familiar with their operation, it was found that these devices were generally insensitive to submicron particles, could only handle very small concentrations, were difficult to calibrate, and were proven inaccurate in many cases. For these reasons, no attempts to make measurements with the devices were made.

A further particle measurement technique (Reference 4), incorporated Mie light scattering theory with the measurement of the extinction of different wavelengths of light which pass through a particle-gas flow. In the arrangement for this technique (Figure 9), a mercury vapor light is focused through a jet of a particle-gas flow and focused on a photomultiplier tube. Measurements of the extinction of two wavelengths, in this case $4358 \text{ \AA}$ and $5461 \text{ \AA}$ are made. These extinction values, along with the refractive index for the particle material, and the thickness of the particle-gas flow through which the beam passes, are the data inputs to a computer program which calculates a field of extinction values at the input wavelengths assuming various mean particle

HAYES INTERNATIONAL CORPORATION

sizes within the flow. The program compares the input extinction values with the computed field and selects a corresponding mean particle size and calculates a concentration.

Measurements with this technique on the output of DOP particles from the ROYCO generator, gave a mean number particles size of 0.63 microns and a concentration of 8.3×10^6 particles/cm³. These values compared well to values obtained with other techniques.

This technique appeared to offer a suitable particle sizing system until further analysis revealed that it would yield inaccurate particle sizes when the particles being measured consisted of a wide particle distribution. It was felt that further improvement of the technique could be achieved through modification of the computer program and extinction measurements to allow for measurements at more wavelengths of light; however, time limitations did not allow this improvement to be made.

Particle Impaction Technique

Another particle measuring technique is based on the principle that a particle in a moving particle-gas flow will impact upon a plate placed in its path provided the inertia of the particle is sufficiently large compared with the drag force exerted on the particle by the air. A device called the cascade impactor which incorporates this principle is shown schematically in Figure 20.

Measurements of DOP and silicon particles were conducted using a 5 stage cascade impactor obtained from Scientific Advances Inc., Columbus, Ohio. This impactor was designed to collect particles in the range of 0.25 microns to 4 microns, each stage collecting a certain particle size distribution within that range.

In making the measurements, a particle-gas flow of 1.05 liters/min (design value) was pulled through the impactor for 1-2 minutes. Afterwards, the mass of material collected on each impactor plate was measured by an infrared absorption technique. The masses were then used to plot 5 points on a size distribution curve. Using the size distribution data and the flow rate data, a concentration could then be calculated.

HAYES INTERNATIONAL CORPORATION

Values of the mean particle size and concentrations for DOP and silicon particles were made with this technique in order to evaluate the shearing jet aerosol generators. This data is shown in Figures 15 and 16. This technique has demonstrated excellent operation although its application is limited to sample taking in low speed flows at near atmospheric pressures. Even with these limitations this technique has offered the most satisfactory results of all particle measuring systems investigated.

HAYES INTERNATIONAL CORPORATION

4.0 FLOW FIELD MEASUREMENTS

The flow field measurements conducted with the LDV system are the most important practical part of the LDV program. These measurements have demonstrated the feasibility of conducting three-dimensional mean velocity measurements in a supersonic wind tunnel flow field and of conducting one-dimensional turbulence measurements in subsonic free jet flow.

The following sub-sections discuss the velocity measurement programs which were undertaken. These programs include: base flow measurements for a clustered engine model, subsonic free jet measurements, and supersonic wind tunnel measurements.

4.1 BASE FLOW MEASUREMENTS FOR A CLUSTERED ENGINE MODEL

This test program was the first attempt to apply the LDV system to the measurement of three-dimensional mean flow field velocities in a wind tunnel environment. Although no velocity data were obtained due to difficulties with the laser, the operational experience which was gained in the LDV alignment and tracer system were useful.

The following segments describe the test facility and LDV system arrangement, the tracer system, and the test results.

The Test Facility and LDV System Arrangement

This test program was conducted at the Arnold Engineering and Development Center (AEDC), Tullahoma, Tennessee. A test cell installed at AEDC which contained a clustered nozzle configuration model (four engine), provided the base flow field in which the measurements were to be conducted. The test cell was designed to provide the four-engine nozzle model with variable ambient pressure to model plenum pressure ratio. This flow variable allowed the simulation of various nozzle exhaust impingement conditions which created different base flow conditions.

HAYES INTERNATIONAL CORPORATION

The four model nozzles were conical with cylindrical shrouds and equally spaced on a 6.6 inch diameter circle. Each nozzle had an area ratio of 3.11 and exit diameter of 2.67 inches. The nozzles were attached to a plenum chamber which could be operated at pressures from 20 to 100 psig. During these tests, the plenum chamber was normally operated at 60 psig with an ambient pressure to model plenum pressure ratio of 26×10^{-4} . A heat shield was located 2.0 inches from the nozzle exit plane giving a base region vent area between the nozzles of 2.0 inches by 2.0 inches. A diffuser was located downstream of the nozzle exhaust at a position which created constant ambient or test cell pressures during model operation. After passing through the diffuser, the model gases were exhausted into a large low pressure exhaust sphere. More complete details of the test facility are given in Reference 11.

The electronic data analysis system (Figure 21) consisted of three spectrum analyzers which allowed for on-line observations of the Doppler signals. In order to record the Doppler signals, the vertical output from each of the spectrum analyzers was connected to a tape deck for recording. Marker frequencies on the spectrum analyzer were to be used to establish the frequency of the Doppler signal. Since no Doppler signals were identified during this program, this electronic system was never properly evaluated.

The relative positioning of the test cell and LDV instrument for alignment is shown in Figure 21. The alignment of the LDV instrument was made with the main or LO beam from the Raytheon LG 12 laser perpendicular to the centerline of engine model. A small diameter scattering jet, which was fixed to a three-dimensional traversing mechanism mounted inside the cell, could be moved to various known positions within the nozzle base region. This jet contained small tracer particles of dioctyl phthalate (DOP) to scatter the LO beam and provide a point from which the LDV instrument could be

HAYES INTERNATIONAL CORPORATION

aligned and a Doppler signal obtained. During the operation of the model flow, the alignment jet was moved to a remote region of the test cell.

The Tracer System

When planning for this test program first began, it was evident that the requirements on the tracer system would present difficult problems. The primary problems were due to the quantity of flow in which tracers were to be injected (9.4 lb/sec from 4 nozzles) and the requirement that the particles be produced in pressures that were above atmospheric (approximately 60 psig). The tracer system that could best meet the test facility requirements was the chemical mixing of ammonia and hydrogen chloride gases to produce ammonium chloride particles. This system offered the ability for mixing the gases within the model plenum chamber at a rate which would provide estimated particle concentrations in the base region of 10^6 particles/cm. A schematic of the gas control system is shown in Figure 22. This system was designed to provide an injection of gases, at the plenum chamber entrance to two of the nozzles. The gases were injected along the inside edge of the nozzle entrance since this was the exhaust flow region which produced the reversed flow into the base. Since only two of the nozzles were injected, the LDV measurements were confined to one half of the base flow region. The system was capable of providing sufficient flows of ammonia and hydrogen chloride gases to produce particle concentrations in the nozzle flow which would provide an estimated 10^6 particles/cm in the base flow region.

The tracer system operation was considered an overall success in its ability to provide sufficient tracer particles. However, several operational problems were noted. These problems included, leaks in the gas regulation system, loss of pressure due to cooling in the ammonia cylinders, and slight corrosion inside the test cell.

HAYES INTERNATIONAL CORPORATION

Due to the toxic nature of the gases used, the leaks which occurred in the system were physically dangerous to the personnel in the area. Strict safety precautions were observed throughout the test program. During the operation of the system, all personnel in the area were required to wear protective gas masks. After a test run, the ammonia and hydrogen chloride gas system was purged with dry nitrogen and all the gas bottles were closed. Whenever a leak was noted, the gas system was immediately closed at the dome regulators with the solenoid operated valves shown in Figure 22.

Due to the fact that ammonia is stored as a liquid at room temperature and a vapor pressure of 114 psig, the injection of the required quantity of ammonia gas into the model plenum chamber at 60 psig proved to be difficult to maintain. As the gas was evaporated, the temperature of the liquid decreased causing a reduction in the bottle gas pressure and a corresponding reduction in flow rate. This problem was solved by heating the ammonia bottles with heater tapes and portable air heaters. Heaters were not required on the hydrogen chloride bottles, since at room temperature the bottles would have a pressure of 613 psig which was enough pressure to maintain the required flow rates.

The corrosion which resulted from the use of this tracer system was found to be less than expected. No tunnel operational difficulties were encountered as a result of the corrosion caused by this tracer system. During the testing period a practice of periodic cleanup of the test cell model was followed in order to minimize any corrosion problems.

Test Results

During the entire test period of AEDC and for many months thereafter, the LDV system was evaluated to determine the operational parameters with which a readable Doppler signal at supersonic flows could be obtained.

HAYES INTERNATIONAL CORPORATION

Such an evaluation was prompted by the fact that no Doppler signals were detected during the AEDC tests. The results of these evaluations and improvements in the LDV system culminated in the demonstration of three-dimensional supersonic LDV measurements at the MSFC 7-inch wind tunnel (Section 4.3).

These evaluations of the LDV system indicated that the major reason for not obtaining a readable Doppler signal was due to the use of an etalon within the laser cavity of the Raytheon LG 12 laser. The use of an etalon to improve the Doppler signal is discussed in Section 2.2. It is noted in that section that unless the etalon is properly aligned the Doppler signal will not be detectable. It is further noted that such an alignment within the Raytheon laser could only be maintained for short time periods. Due to the transient thermal conditions which caused slight movements of the etalon. During the tests it was found that manual adjustment of the etalon could cause a loss in the Doppler signal obtained from the alignment jet, however it was not until after the tests that the thermal movements of the etalon were established.

Although no Doppler measurements of the base flow was made, several significant results were made. These results are listed below.

- (1) The alignment of the instrument could be maintained through the windows of the test cell.
- (2) Measurements of the scatter intensity received during the tests indicated that the particle concentrations produced by the tracer system were sufficiently large to obtain Doppler signals.
- (3) The particles in the flow caused fogging of the test cell windows to the extent that the windows became opaque. Such fogging was alleviated by the use of window guards which kept the reverse base flow from striking the window, but passed the scatter and LO beams.

HAYES INTERNATIONAL CORPORATION

- (4) The small alignment jet within the test cell proved to be a necessary and important part of the LDV system for locating and aligning the instrument relative to the model.

These results are considered significant since they provide further operational understanding and experience with the LDV system.

4.2 SUBSONIC FREE JET MEASUREMENTS

In order to demonstrate the ability of the LDV system to make turbulence measurements, a series of one-dimensional turbulence and mean velocity measurements within a free jet were conducted. These measurements are discussed in the following segments which describe the test arrangement, the electronic system, and the test results.

Test Arrangement

The test arrangement for conducting the free jet measurements is shown schematically in Figure 23. In this arrangement, a Raytheon Model LG 12 argon laser provided light of $4880 \text{ \AA}$ at powers between 0.2 and 0.3 watts. This light, referred to as the LO beam, was passed through a beam expander, then reflected off a mirror and through a lens which focused the beam in the free jet flow.

An aluminum plenum chamber, approximately 3 feet long and 3 inches in diameter, with a 0.5 inch diameter smooth entrance nozzle provided the free jet flow. An exhaust duct 1.5 feet in diameter was located approximately 1.5 feet from the jet exit to keep the test area free of tracer particles.

The relative alignment between the free jet flow and the laser and LDV instrument was such that the velocity component measured by the instrument was in a direction parallel to the centerline of the free jet assuming that the velocity component parallel to the laser beam is approximately zero. This alignment was accomplished by (1) making the laser beam perpendicular to the jet centerline and (2) making the plane formed by the centerline of the LO tube and the centerline of scatter tube No. 3, lay along the centerline of the jet.

During these measurements, the field stop and front aperture within the scatter tube of the LDV instrument were at 25.0 microns diameter and 15.0 mm diameter respectively. These values were found to provide a scattering volume comparable to hot wire anemometer probe sizes (Section 2.5.1).

HAYES INTERNATIONAL CORPORATION

The relative movement of the LDV scattering volume and the hot wire probe used during the tests was accomplished by movements of two cross-blocks on which the jet was mounted. These blocks allowed for movements in the X and Y directions.

The tracer particles were dioctyl phthalate (DOP) and were produced by an aerosol generator manufactured by ROYCO Instrument Company. This generator produces the particles by forcing compressed air through small jets immersed in the fluid. Measurements of the particle size and concentration produced by this generator are given in Figures 15 and 16.

Electronic Systems

In order to make comparisons of the free jet measurements that were conducted, two electronic systems were employed. One system consisted of the components necessary for making mean velocity and turbulence measurements with the LDV system and the other system consisted of the instrumentation necessary for making similar flow field measurements with the hot wire anemometer.

The electronic system necessary for detecting and processing the Doppler signal consisted of the following components:

- (a) An RCA 8645 photomultiplier tube on which the photomixing occurs.
- (b) A wide band amplifier which increased the signal strength to approximately .1 - .4 volts RMS.
- (c) Frequency tracker (described in Section 2.4), which provided a DC voltage corresponding to the mean flow velocity and an AC voltage corresponding to the velocity fluctuations (turbulence).
- (d) A variable band-pass filter to limit the tracker output signals to be the same frequency range as the hot wire system.
- (e) A true RMS voltmeter and tape deck which provided for either a direct reading or recording of the tracker AC output.

HAYES INTERNATIONAL CORPORATION

The hot wire anemometer equipment consisted of a DISA 55A01 constant temperature anemometer unit. The probe used with this unit contained a signal wire, 0.66 mm in length and 0.005 mm in diameter. This instrument also provided a mean voltage reading which was a measure of the mean flow velocity and a fluctuating voltage read on a RMS voltmeter which was a function of the flow turbulence. This instrument is considered accurate to approximately $\pm 3\%$ for measurements of local isentropic turbulent intensities of less than 20%.

Test Results

Measurements of the mean velocity and turbulence within the free jet were made with both the LDV and hot wire systems. For the results presented the mean core velocity was 173 ft/sec and the Reynolds number based on the jet diameter was 47,000.

Figure 24, which compares hot wire and LDV turbulence data down the centerline of the nozzle, show good agreement especially in the potential core ($x/D < 4$). A "hump" is noted in the LDV and hot wire profiles which is not present in the data of Corresin and Uberoi (Reference 9). This hump is probably a characteristic of the flow system measured.

Figure 25 shows a comparison of LDV and hot wire mean velocity profiles at $x/D = 2.0$. Excellent agreement between the data is noted.

A comparison of turbulent intensity profiles at $x/D = 2.0$ is presented in Figure 26. These curves reflect the range of data for four sets of hot wire data and two sets of LDV data. The average uncertainty of the hot wire and LDV data is 5.5% and 8.2% respectively. The LDV data given was not continued past the point at $Y/R = .96$ due to the intermittency of particle concentrations caused by the mixing of the seeded flow air with the surrounding ambient air. This intermittency produces a Doppler signal which is not continuous enough to provide statistical information of the turbulent fluctuations present. The air surrounding the jet would have to be seeded with tracer particles in order to overcome this problem.

HAYES INTERNATIONAL CORPORATION

Several power spectral density curves of the hot wire and LDV data at the same positions in the flow are shown in Figures 27 and 28.

These curves were obtained from a computer program which analyzed .5 sec. samples of the data at a bandwidth of 27.1 Hz. A close agreement between the hot wire and LDV distributions is noted for the points presented.

Comparisons of the data obtained with the LDV instrument and hot wire anemometer show good agreement. The major source of error in the measurements appeared to be a result of inaccurate positioning of the jet; however, additional measurements are needed to substantiate this point.

4.3 SUPERSONIC WIND TUNNEL MEASUREMENTS

In order to demonstrate the ability of the LDV system to perform three-dimensional mean velocity measurements in a supersonic flow field, a series of measurements at the NASA Marshall Space Flight Center 7-Inch Wind Tunnel were planned and conducted. The test objectives were (1) to make three-dimensional velocity measurements within a wing-tip trailing vortex at $M = 1.99$ in the free stream, (2) to establish an electronic system suitable for making such measurements, and (3) to evaluate a tracer system which can be used in the wind tunnel environment. The following segments describe the test facility, the LDV instrument alignment, the electronic system, the tracer system, and the velocity measurements.

The Test Facility

The MSFC 7-Inch Wind Tunnel is an atmospheric to vacuum blowdown tunnel (Figure 29) with a Mach number range from 0.1 to 5.00. Mach numbers from 0.1 through 1.0 are obtained with convergent nozzle blocks and Mach numbers above 1.5 are obtained with fixed, contoured, inter-changeable nozzle blocks. The tunnel air supply consists of atmospheric air which is dried and stored in a tank provided with a rubber diaphragm to maintain constant supply pressure during blowdown.

A test section, 7" x 7", is accessible by complete side wall removal, accomplished by hydraulic cylinders. For the LDV tests, a 6% - thick biconvex constant cross-section wing with an aspect ratio of 2.7 was attached to the tunnelside wall (door) at a $+6^\circ$ angle of attack. The trailing edge of the wing was at the upstream edge of the sidewall observation window and the wing-tip was along the tunnel centerline.

A schematic of the tunnel and the LDV system arrangement is shown in Figure 29. Pictorial arrangement of the LDV instrument stand and electronic components relative to the wind tunnel test section are shown in Figures 3 and 4.

During these measurements, the nozzle blocks, which provided a test section Mach number of 1.99, were installed. It was noted that with this nozzle installed, the wing model position was such that it was not in the fully expanded region of the nozzle; however, since the primary interest was concerned with the generation of a supersonic trailing vortex rather than the simulation of a particular known velocity field, the consequences of such positioning on the flow field were ignored.

The LDV Instrument Alignment

Prior to conducting the wind tunnel tests, several modifications and optical measurements were made on the LDV instrument. The modifications included removal and recoating of all optical components, the additions of optical path length equalizers (Section 2.5.2) in each scatter tube, and the insertion of an acousto-optical modulator (Section 2.3) in the LO tube. After these modifications were made, the instrument was completely realigned and the optical operation with the modifications was defined. This work was conducted in order to assure optimum operation with a minimum of alignment difficulties during the test.

Alignment of the LDV system proved to be much easier than during previous tests. The system was first mechanically aligned with the tunnel so that movements of the cross blocks on the LDV stand remained parallel to the tunnel coordinate system shown in Figure 5. Next, the laser beam and LDV instrument were aligned with the use of a small exit diameter (1/32 inch) free jet. This jet was designed to provide a known scattering point from which a Doppler shifted frequency could be obtained. The jet was attached to the tunnel sting mechanism so that it could be moved into a known position for periodic checks of the instrument alignment, and moved to the tunnel floor during tunnel operation.

Using the small scattering jet, the instrument was aligned and the scatter tube optics were set to provide the smallest scattering volume, (field stop at 25.0 microns diameter and front aperture at 15.0 mm diameter).

The smallest scattering volume was used throughout the test program.

During the initial alignment, the acousto-optical modulator was set to provide a frequency shift in the LO beam of 57.6 MHz. Such a shift was necessary to determine the direction of the velocity components (Section 2.3).

The alignment procedure as well as the system operation was considerably improved by the use of the increased laser power (2.5 watts at 5145⁰A) which was available from the CRL Model 53 laser. This laser provided sufficient scattering power for achieving a 10 db increase in S/N over that obtained previously with a laser power of .25 watts for the same conditions (i. e., jet speed, particle size and concentration, and optical setting). The use of the increased laser power allowed a reduction of the tracer concentration requirement from approximately 10^8 particles/cm³ to $10^5 - 10^6$ particles/cm³.

Several Doppler signal measurements also indicated that even further concentration reductions may be possible in future tests. These measurements showed that S/N of up to 10 db could be achieved from the alignment jet for periods up to 20 minutes after the particles production was ceased. These qualitative measurements indicated that it may be possible to obtain readable Doppler signals with particle concentrations approaching that resulting from natural contaminants.

The Electronic System

The electronic system, used to process, identify, and record the mean Doppler frequencies for each of the three scatter tubes of the LDV instrument, is shown schematically in Figure 30. In this system, the three Doppler frequencies were initially processed by three spectrum analyzers. An ability to improve the S/N displayed by the spectrum analyzers was provided by a signal analyzer (Hewlett-Packard Model 5480) which processed the vertical output of each of the spectrum analyzers. The S/N improvement depended on the number of signal samples which the instrument processed. The maximum number of samples per unit time which the instrument was able to process was

100 samples/sec which corresponded to a sweep rate of 1.0 millisecc/cm. In order to provide the signal analyzer with the maximum number of samples/sec from the spectrum analyzer, it was necessary to increase the sweep rate of the spectrum analyzers from 3.0 millisecc/cm to 1.0 millisecc/cm. The electronic modifications required to increase the sweep rates are given in Reference 8. External synchronization of the spectrum analyzers and the signal analyzers was also necessary in order to ensure that the signal analyzer achieved the maximum signal availability. Thus, for any given time period for Doppler signal input (i. e., tunnel test time), the electronic system was operating at its maximum capacity to process the signal spectrum and improve the S/N.

During the operation of the wind tunnel, the three Doppler frequency spectrums were processed and stored in the magnetic core storage of the signal analyzer. When the tunnel operation was complete, the stored signal spectrums were recorded from the magnetic core storage using an X-Y penplotter. Following the tunnel operation, the three noise spectrums were likewise processed and plotted with the X-Y recorder. Comparisons of the noise and Doppler signal spectrums were then made in order to identify the Doppler signal. The frequency of the Doppler signal was established with the use of marker frequencies which were produced by the acousto-optical modulator (Section 23).

Typical spectrums showing the Doppler frequencies and marker frequencies for each of the three scatter tubes of the LDV instrument are shown in Figure 31. Note that in this Figure the noise spectrum has been graphically subtracted from the signal spectrum in order to make the Doppler frequency spectrum more clearly distinguishable with a flat base frequency noise spectrum. The normal spectrum traces recorded from the electronic system did not have a flat frequency response over the spectrum. In some cases, the Doppler frequencies were difficult to identify due to the uneven frequency response of the system. This uneven or non-flat frequency response was caused by the amplifiers which were used. The use of improved wide band amplifiers such as the Hewlett-Packard

Model 35002 A or equivalent would be a significant improvement in the electronic system for future testing.

The Tracer System

The tracer system used for these tests produced liquid tracer particles of silicon liquid by forcing compressed air through a series of shearing jets immersed in a bed of the liquid. The design and operation of the system is discussed in Section 3.0 and a picture of the particle generator installed at the tunnel test facility is shown in Figure 18. Measurements of the particle concentrations and size at this generator outlet indicated that particle concentrations of 1.94×10^8 particles/cm³ with a massmean particle size of 1.08 microns were produced.

With the use of the increased laser power (2.5 watts) provided by the CRL Model 53 laser and the S/N improvements provided by the signal analyzer, it was found that reductions in particle concentrations at the test section could be made without significant reduction in signal level. For this reason, the operation of the particle generator and the air supply sphere was such that the concentration within the test section was reduced to approximately 10^6 particles/cm³. Estimates of the particle concentration within the sphere for a typical series of runs is shown in Figure 18 along with the estimated particle concentration at the test section which results from the decreased density in that region. In these estimations, no corrections for particle agglomeration, fallout, or loss on the test cell entrance screens were made. However, note that the measured sphere concentration compares well to the estimated value at the run shown.

During the testing period, no adverse effects of the tracer liquid (silicon) on the tunnel facility were noted. The only difficulty encountered with the use of the liquid tracers was due to a "streaming" of the liquid along the test cell windows. In several runs this "streaming" passed along the test cell window in the region through which the LO beam was passing.

The "streaming" liquid caused a slight optical deflection of the LO beam resulting in a temporary loss of alignment. A possible solution to this is the use of some technique for "tripping" the boundary layer along the window, thus keeping the liquid from collecting and "streaming" down the window.

The Velocity Measurements

The velocity measurements taken during this test were made in a Y-Z plane (Figure 5) located one chord length downstream of the wing model. The tunnel was operated at a free stream Mach number of 1.99, and velocity profiles in the Y and Z directions were made. These profiles were concerned with defining the three-dimensional velocity changes which occur within the region of the trailing vortex. Figures 33, 34, 35, and 36 show the velocity profiles for the Y traverse and Figures 37, 38, 39, and 40 show the velocity profiles for the Z traverse. The velocity points in the positive Z direction of Figures 37, 38, 39, and 40 are possibly inaccurate as a result of the partial blockage of the tunnel entrance during the runs in which the measurements are made. Shortly after these measurements were made, it was found that the air supply bladder had torn from the sphere and was partially blocking the tunnel entrance. This not only cast doubt on the test points noted, but also caused the test program to be discontinued before the Z profile was satisfactorily completed.

The velocity data presented was calculated with the use of a computer program given in Reference 8, which solves the three-dimensional LDV equations given in Table I.

Figure 36, which is the w velocity component profile for the Y traverse, shows the existence of the trailing vortex and provides some definitions of its size and position. It is seen to have a counterclockwise rotation, looking in the negative X direction, to be approximately .125 inches in diameter in the most intense region and to be located approximately 0.25 inches inboard from the wing tip at one chord length (2.5 inches) downstream. The position and size of the vortex were found to be in good agreement with other measurements

(Reference 10) made with conventional techniques at $M = 1.6$. The mean velocities in the free stream for both the Y and Z profiles were also found to be in good agreement with the calculated free stream velocity (1680 ft/sec) for $M = 1.99$ flow assuming standard conditions.

For convenience and ease in aligning the LDV instrument, the LO beam was passed through the wind tunnel test section at a 90° angle to the tunnel center line. This alignment arrangement caused the instrument sensitivities to be different for the u, v, and w velocity components. With this arrangement, the sensitivity of the instrument to the v velocity component was approximately an order of magnitude smaller than the sensitivity for either the u or w components. This lack of sensitivity causes correspondingly large uncertainties in the v component for any frequency reading inaccuracy. Assuming a frequency reading inaccuracy of ± 1.0 MHz in each of the three frequency components, calculations of the corresponding deviations in the velocity components were made. Such frequency inaccuracies would cause a standard deviation inaccuracy in the v component of ± 72.5 ft/sec. This uncertainty is evident in the v component profiles for both the Y and Z traverse. Neither of these profiles show the expected velocity trends for rotational flow.

The sensitivity or accuracy of the LDV system for the v component can be improved by two methods. One method would be to increase the electronic frequency accuracy. This would result in a corresponding improvement in the v component accuracy. For example, if the frequency reading accuracy was ± 100 KHz then the standard deviation inaccuracy in the v component would be only ± 7.25 ft/sec. Another method for improving the v component sensitivity would be to arrange the laser beam and instrument at different angular alignments. In order to define these angular alignments, an evaluation of the LDV relationships of Table I must be conducted. This evaluation would be aimed at determining the sensitivity of the instrument components for various angular alignments. Due to time limitations in this test, these methods for improving the system were not investigated; however, these methods should be investigated

in order to determine improvements in accuracy which can be achieved in future measurements.

For the objectives of this program, i. e. , the demonstration of the LDV system to perform three-dimensional mean velocity measurements in a supersonic flow field, the measurements which were made clearly demonstrated such a performance. With the inclusion of flatter response amplifiers in the electronic processing loop and an increased sensitivity in the v velocity component, the LDV system should be a useful tool for making accurate three-dimensional mean velocity measurements in supersonic flow fields.

5.0 CONCLUSIONS

The application of the LDV system during this program has demonstrated that the system is capable of conducting three-dimensional mean velocity measurements in a supersonic flow field and of conducting one-dimensional turbulence measurements in subsonic free jet flow. The developmental testing which defined the optimum operating conditions for the above subsonic and supersonic measurements can be summarized as follows:

- (1) The scattering volume size was found to be compatible with conventional gas measurement probes when the field stop and front aperture of the scatter tube was at 25 microns and 15 mm respectively.
- (2) The minimum scattering intensity for which reasonable signal to noise levels (15 db) can be expected is 1.0×10^{-9} watts. The LO power to be mixed with the scatter power should be at least 5 times as large, as long as the photomultiplier tube is not saturated.
- (3) In order to ensure optimum S/N levels from the heterodyne of the scatter and LO beams, it is essential that the coherence of the two beams be maintained. This is best achieved through path length equalization of the scatter and LO beams.
- (4) The tracer particles which will best represent the gas flow should have a low mass density and be submicron in size. The shearing jet aerosol generator provides the best technique for tracer production for use in the LDV system.
- (5) The increase in laser power (2.5 watts) provided by the CRL laser allowed for operation of the system over a wider range of tracer concentrations, i.e., the required tracer concentration could be reduced by several orders of magnitude without appreciable signal loss.

During the tests program, several areas for improvement were also defined as follows:

- (1) Improvements in the angular arrangement of the instrument and in the electronic frequency measuring accuracy should be made in order to improve the sensitivity of the system to the u velocity component.
- (2) The erroneous signals (modulator frequencies and mode beat frequencies) on the PM tube spectra should be eliminated or blocked before the frequency tracker units can be usefully incorporated into the LDV system.
- (3) Amplifiers with a flatter frequency response should be incorporated into the electronic networks to allow for easier identification and tracking of the Doppler signals.
- (4) Further measurements of the particle concentrations at or near the position where the LDV velocity measurements are made, are necessary in order to clearly determine the minimum particle concentration at which measurements can be made.

REFERENCES

1. Morrison, L. K., "A Study of Design Parameters for a Laser Velocity Instrument," Lockheed TM 54/20-202, December 1968.
2. Berman, Neil S., "Particle-Fluid Interaction Corrections for Flow Measurements with a Laser Doppler Flowmeter," Arizona State University Engineering Report for NASA, Contract No. NAS8-21397.
3. Echols, W. H., and Young, J. A., "Studies of Portable Air-Operated Aerosol Generators," NRL Report 5929, July 1963.
4. Tankersley, B. C., "An Optical Technique for Determining the Equivalent Size and Concentration of Carbon Particles in Hydrocarbon Flames," Doctoral Dissertation, University of Alabama, 1969.
5. Rolfe, E. and others, "Laser Doppler Velocity Instrument," NASA CR-1199, December 1967.
6. Huffaker, R. M. and others, "Application of Laser Doppler Velocity Instrumentation to the Measurement of Jet Turbulence," Unpublished.
7. Forman, J. W., "Optical Path Length Difference Effects on Photomixing with Multimode Gas Laser Radiation," Brown Engineering Co., Research Report.
8. Craven, C. W., "Optical Measurement of Multiplume Interaction," Lockheed Final Report for NAS8-21285, January 1970.
9. Corrsin, Stanley and Uberoi, Mahinder S., "Further Experiments on the Flow and Heat Transfer in a Heated Turbulent Air Jet," NACA Report 998, 1950.
10. Davis, Theodore, "The Measurement of Downwash and Sidewash Behind a Rectangular Wing at a Mach Number of 1.6," Journal of Aeronautical Sciences, May 1952.
11. Brewer, E. B., and C. E. Craven, "Experimental Investigation of Base Flow Field at High Altitude for a Four-Engine Clustered Nozzle Configuration," NASA TN D-5164, May 1969.

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} -2 \cos\psi \sin^2 \left(\frac{\alpha}{2} \right) & \sin\alpha & -2 \sin\psi \sin^2 \left(\frac{\alpha}{2} \right) \\ \cos\alpha \cos\psi - \frac{\sqrt{3}}{2} \sin\alpha \sin\psi - \cos\psi & -\frac{1}{2} \sin\alpha & \sin\psi \cos\alpha + \frac{\sqrt{3}}{2} \sin\alpha \cos\psi - \sin\psi \\ \cos\alpha \cos\psi + \frac{\sqrt{3}}{2} \sin\alpha \sin\psi - \cos\psi & -\frac{1}{2} \sin\alpha & \sin\psi \cos\alpha - \frac{\sqrt{3}}{2} \sin\alpha \cos\psi - \sin\psi \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{-\lambda \sin^2 \left(\frac{\alpha}{2} \right)}{3 \sin\alpha \sin^2 \left(\frac{\alpha}{2} \right)} \begin{bmatrix} \frac{1}{2} \sin\alpha \cos\psi & \sqrt{3} \sin\psi \sin^2 \left(\frac{\alpha}{2} \right) + \frac{1}{2} \sin\alpha \cos\psi & -\sqrt{3} \sin\psi \sin^2 \left(\frac{\alpha}{2} \right) + \frac{1}{2} \sin\alpha \cos\psi \\ -2 \sin^2 \left(\frac{\alpha}{2} \right) & \sin^2 \left(\frac{\alpha}{2} \right) & \sin^2 \left(\frac{\alpha}{2} \right) \\ \frac{1}{2} \sin\alpha \sin\psi & -\sqrt{3} \cos\psi \sin^2 \left(\frac{\alpha}{2} \right) + \frac{1}{2} \sin\alpha \sin\psi & \sqrt{3} \cos\psi \sin^2 \left(\frac{\alpha}{2} \right) + \frac{1}{2} \sin\alpha \sin\psi \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$$

Table I. System of Equations Relating Doppler Shifts to Velocity Components for the LDV

TABLE II. SUMMARY OF TRACER MATERIALS INVESTIGATED

MATERIAL	MANUFACTURER	FORM	PARTICLE SIZE	SPECIFIC GRAVITY	REFRACTIVE INDEX	\$ COST
Polystyrene	Dow Chemical Co.	Solid in H ₂ O solution	0.50 - 1.1 μ	1.04 - 1.09	1.59	15.10/gm
Silica	Cabot Inc.	Solid	0.015-.002 μ	2.10	1.550	.85/lb
Calcium Carbonate	Wyandotte Chem.Co.	Solid	0.10 - 0.35 μ	2.65	1.658	.10/lb
Fluorinated Ethylene Propylene (FEP)**	Liquid Nitrogen Processing Corp.	Solid	0.7 μ	2.17	NA*	15.90/lb
Vinyl Chloride Homopolymer (Geon)** (6 types)	B.F. Goodrich Chemical Co.	Solid	0.25 μ	1.40	NA	.42/lb
Polytetrafluoroethylene (TFE)**	Whitford Chemical Corp.	Solid	~1.0 μ -	2.17	NA	6.10/lb
Graphite	Ultra Carbon Corp.	Solid	1.0	1.9 - 2.3	NA	1.50/lb
Diocetyl Phthalate	Union Carbide Co.	Liquid	Depends on Generator	0.98	1.48	1.70/gal
Silicon Fluid	Dow Corning Corp.	Liquid	Depends on Generator	0.95	1.40	13.00/gal
Teflon Particles in Freon	Miller Stephenson Company	Liquid-Solid	15% less than 2.0 μ	2.17 for particle	NA	6.00/lb
Ammonium Chloride	Formed by mixing gaseous NH ₃ and HCl	Solid	Average 1.2 μ	1.52	1.642	.75/lb

*NA - NOT AVAILABLE

** - TESTED IN FLUIDIZED BED

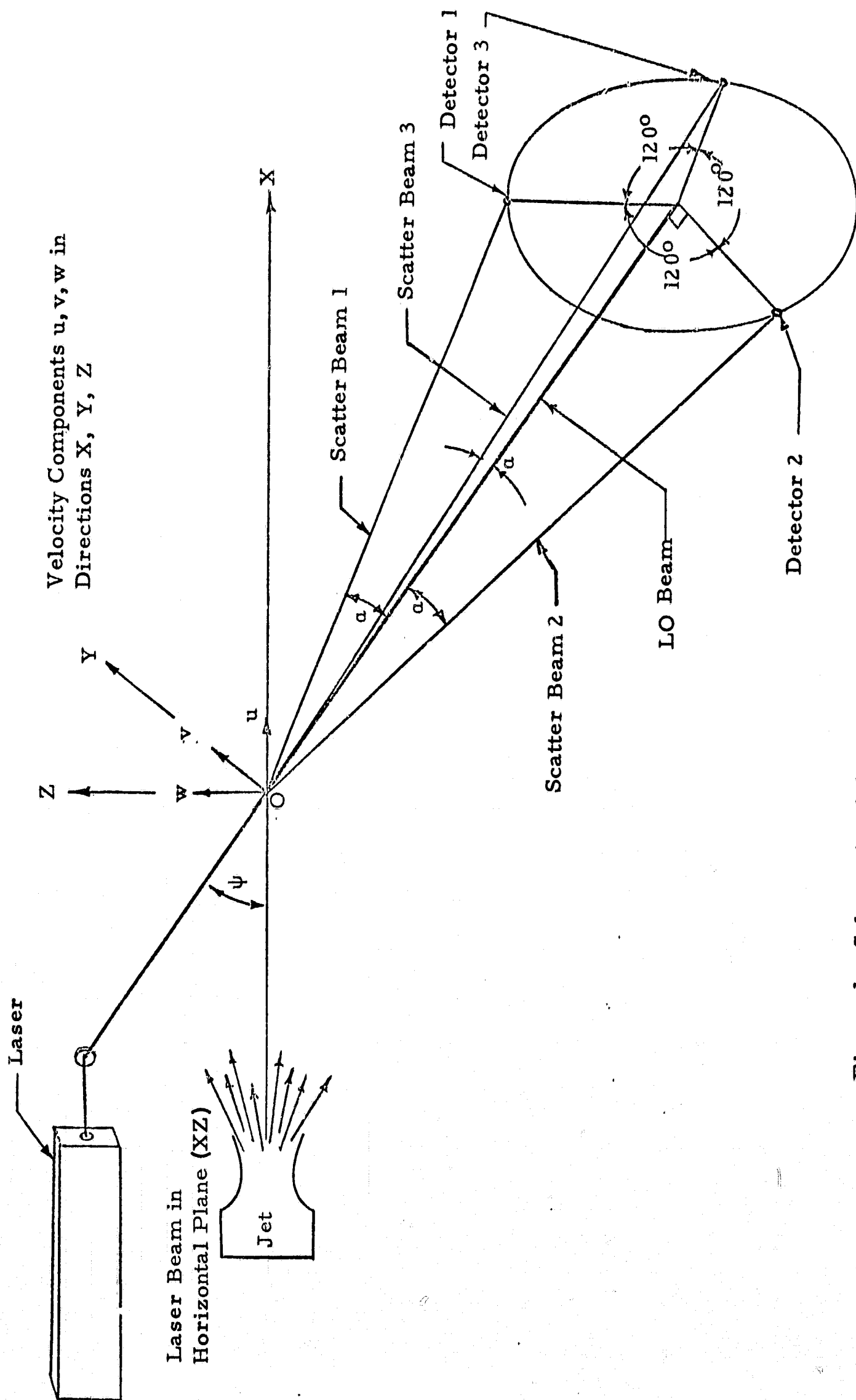


Figure 1. Schematic of the Three-Dimensional Laser Doppler Velocimeter and its Angular Alignment Relative to a Jet Flow

Notes:

- (1) AS = Apperture Stop
- (2) BSP = Beam Splitting Prism
- (3) FS = Field Stop
- (4) L = Lens
- (5) P = Polarizer
- (6) RP = Refractor Plate

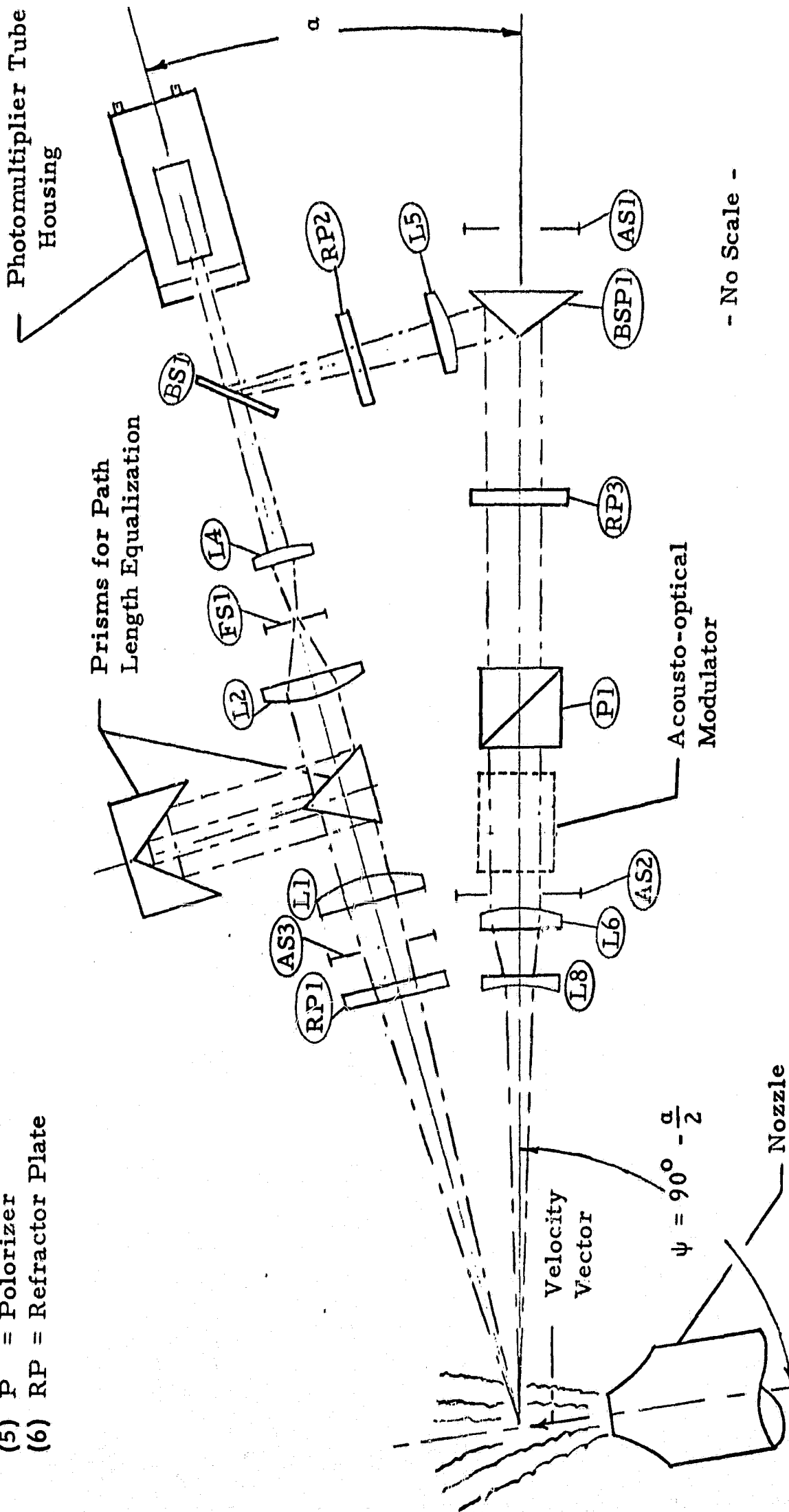


Figure 2. Schematic of One Component of the Three-Dimensional LDV Instrument

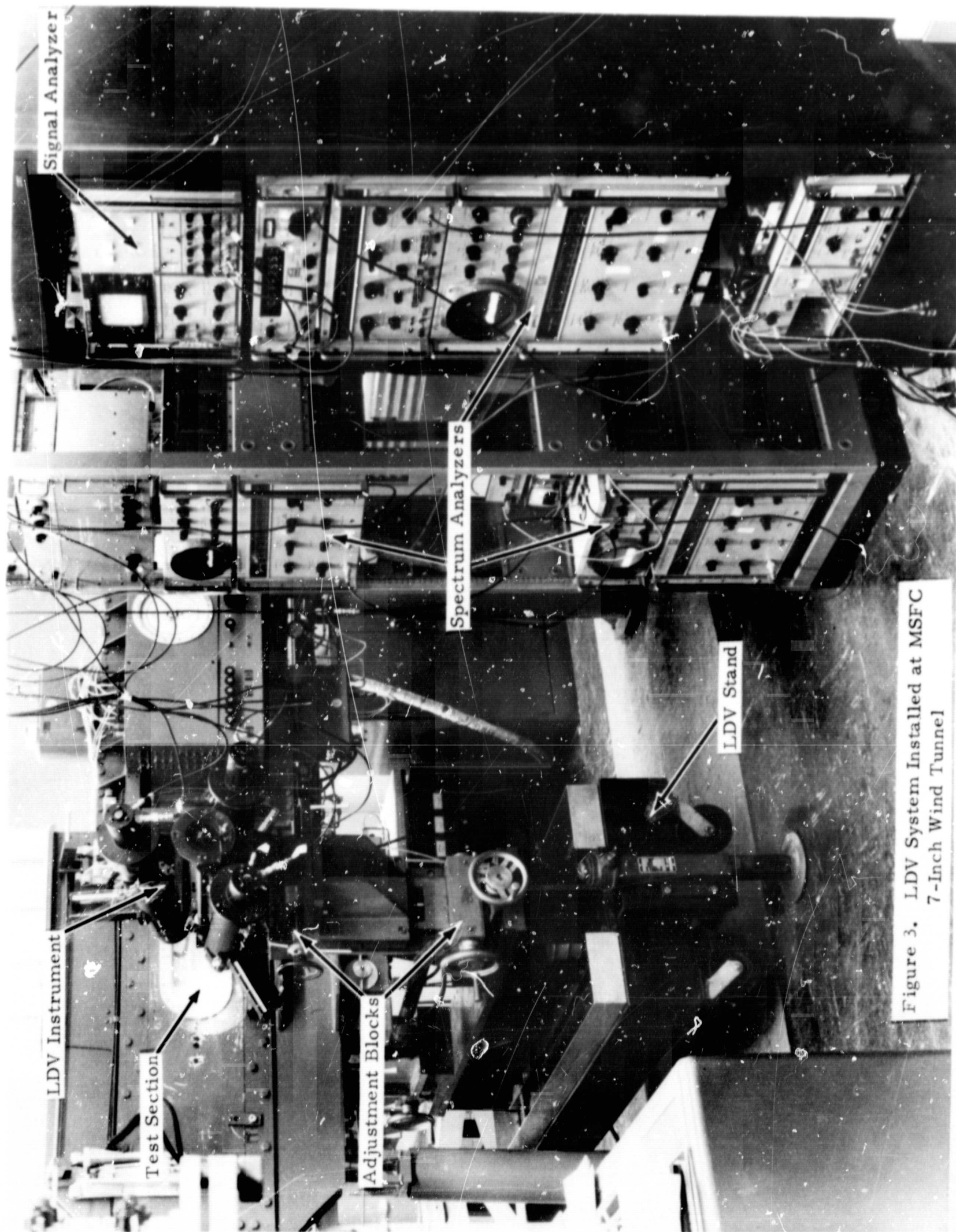


Figure 3. LDV System Installed at MSFC
7-Inch Wind Tunnel

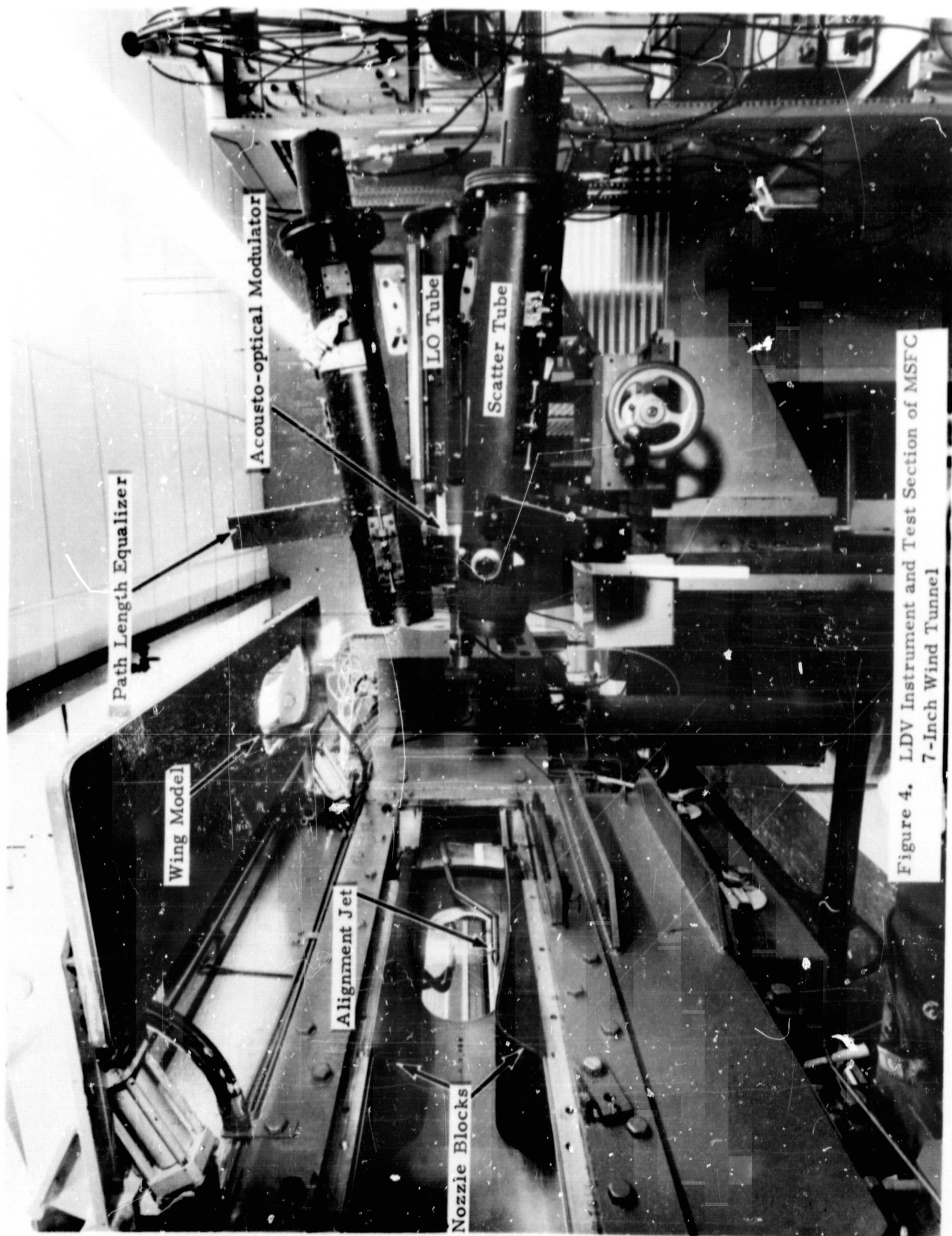


Figure 4. LDV Instrument and Test Section of MSFC
7-Inch Wind Tunnel

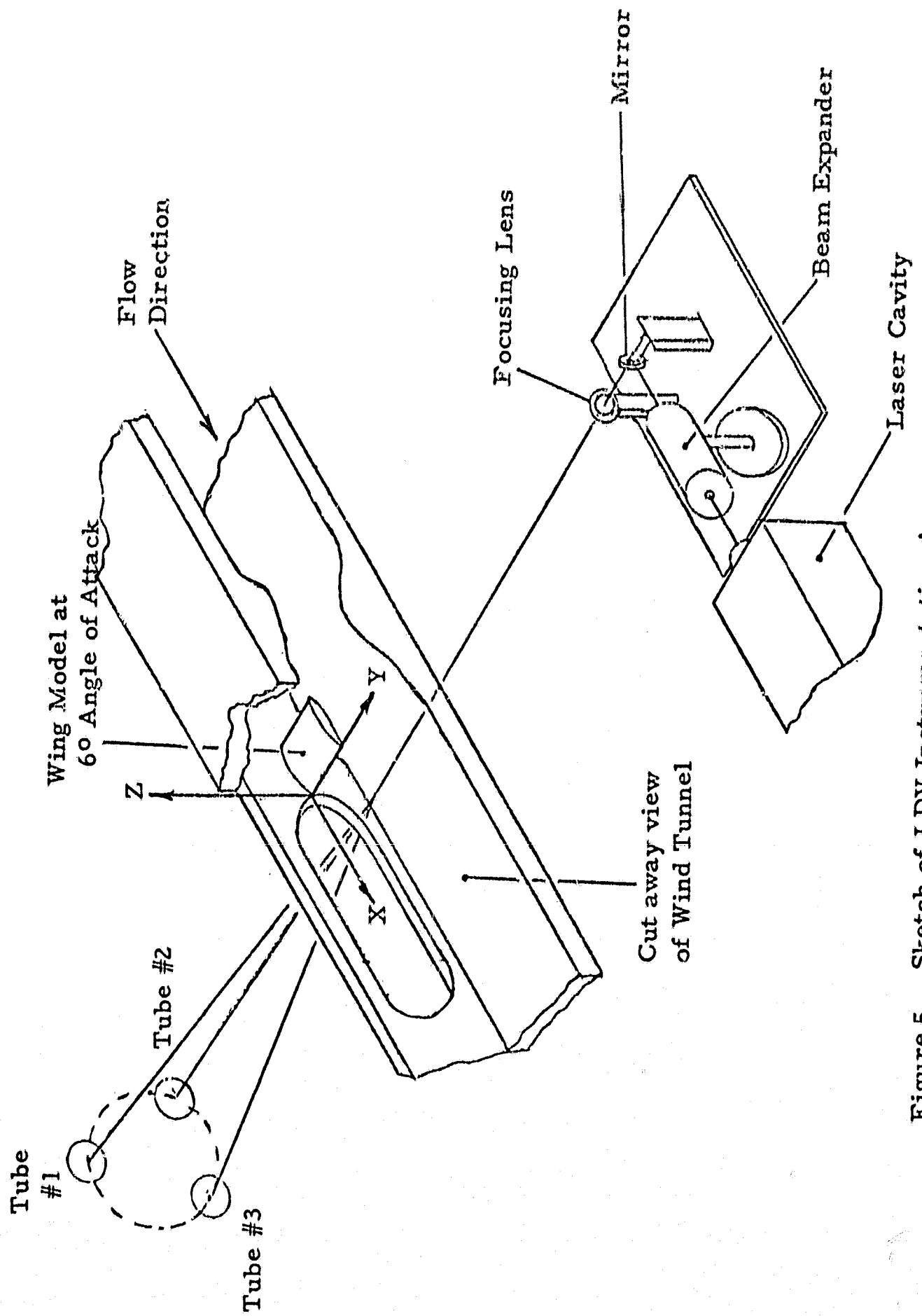


Figure 5. Sketch of LDV Instrumentation Arrangement Relative to Tunnel Coordinate System

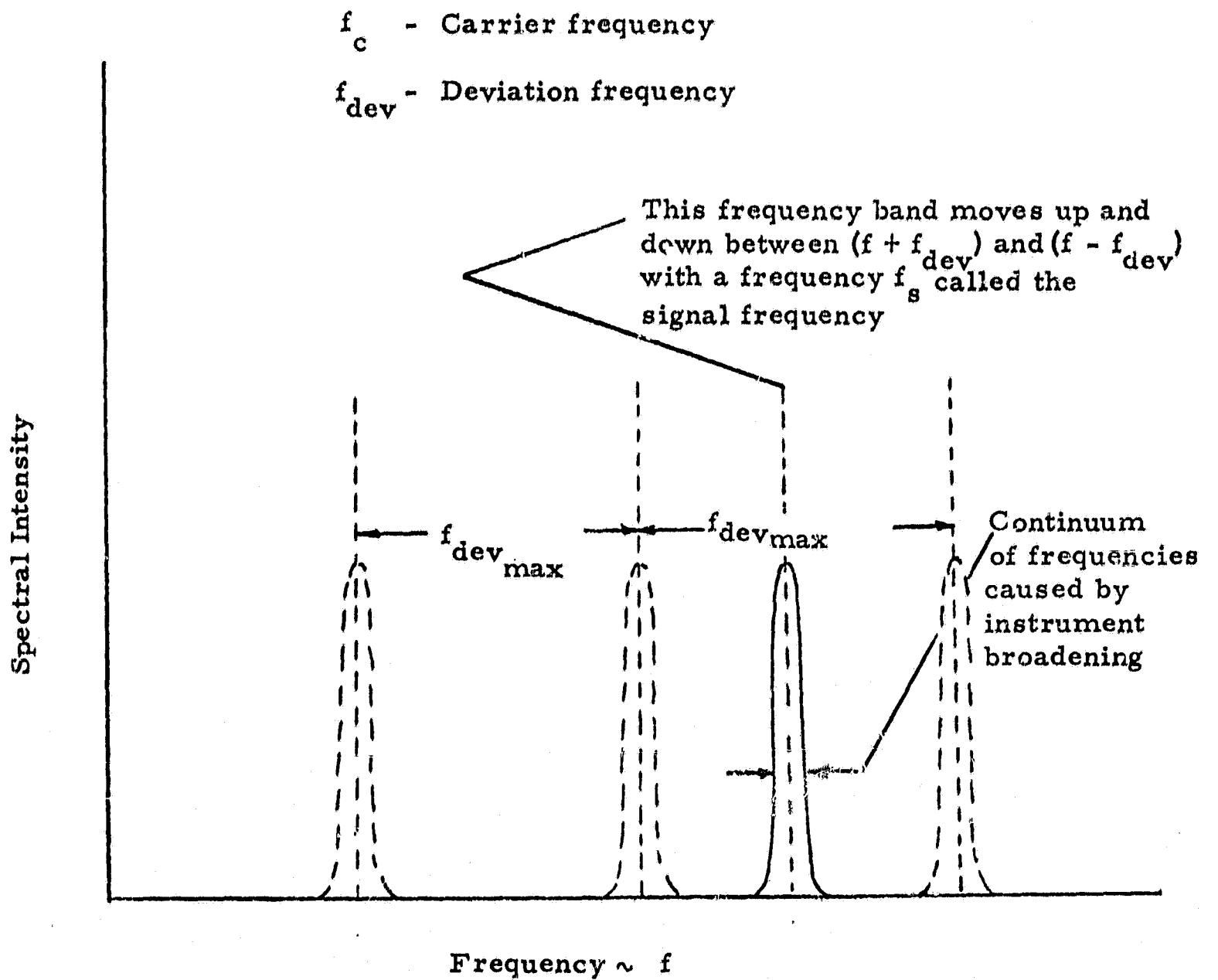


Figure 6. Schematic Representation of Doppler Signal

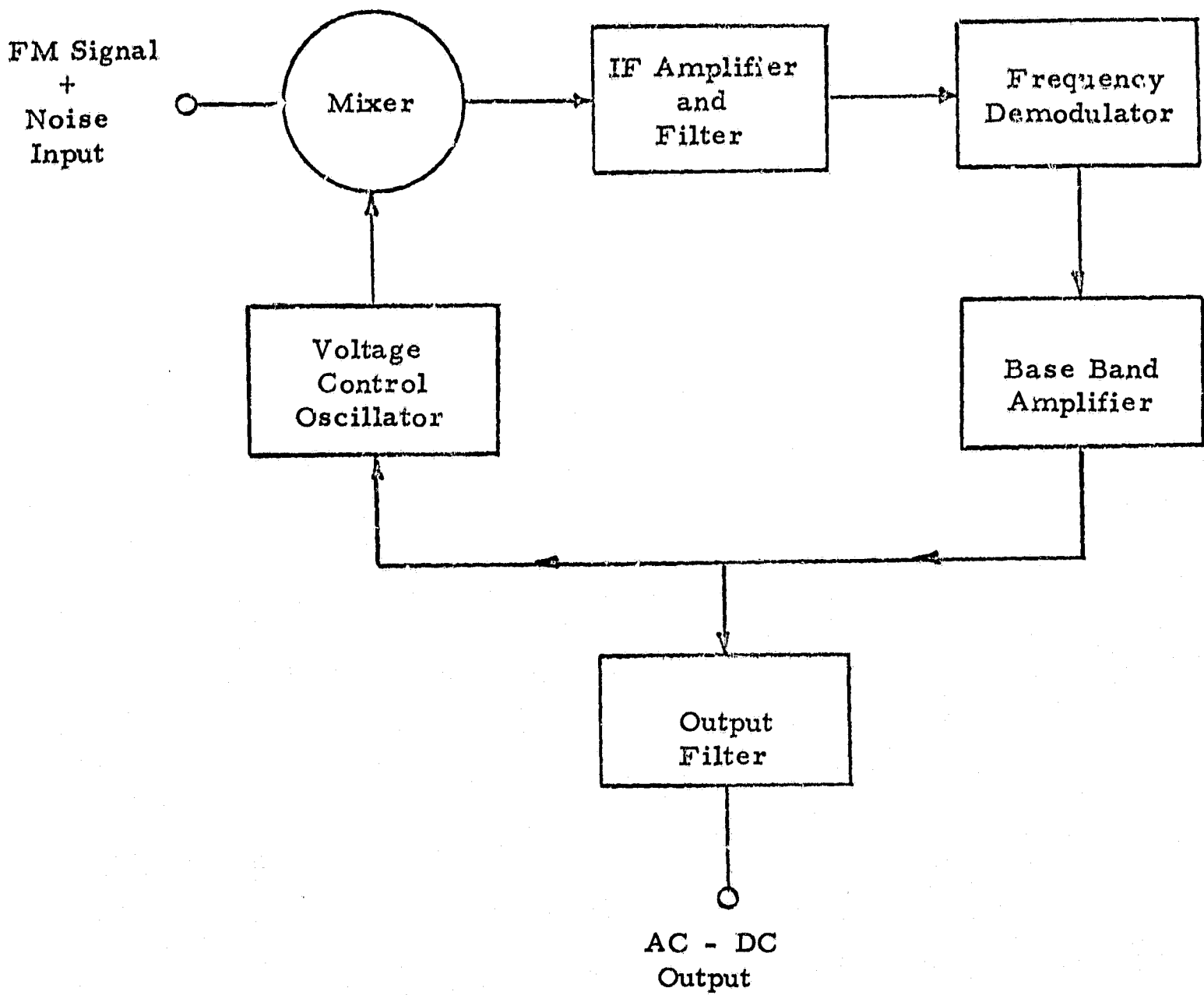


Figure 7. Basic Block Diagram of Frequency Tracker

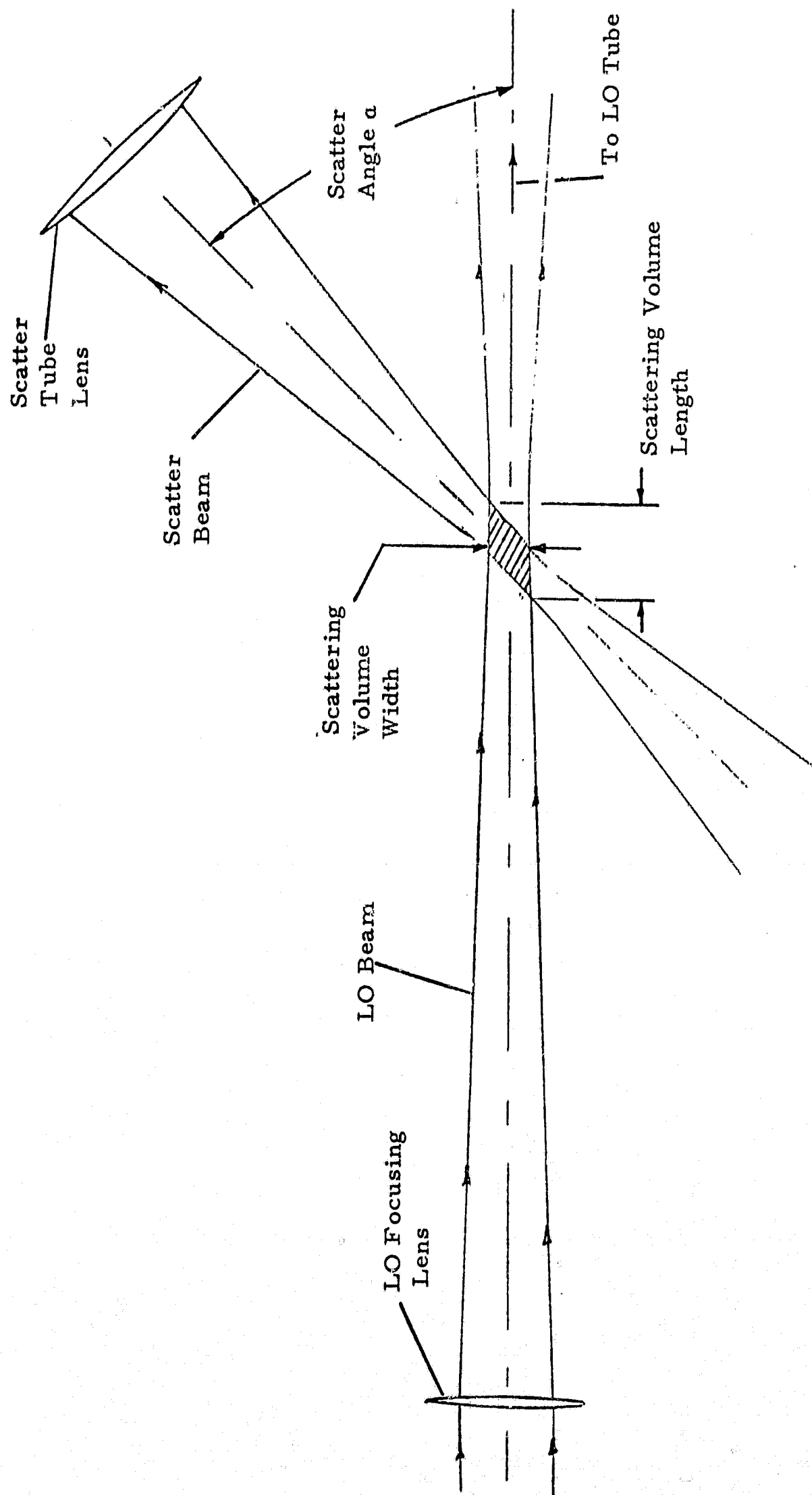


Figure 8. Optical Schematic of LDV Scattering Volume

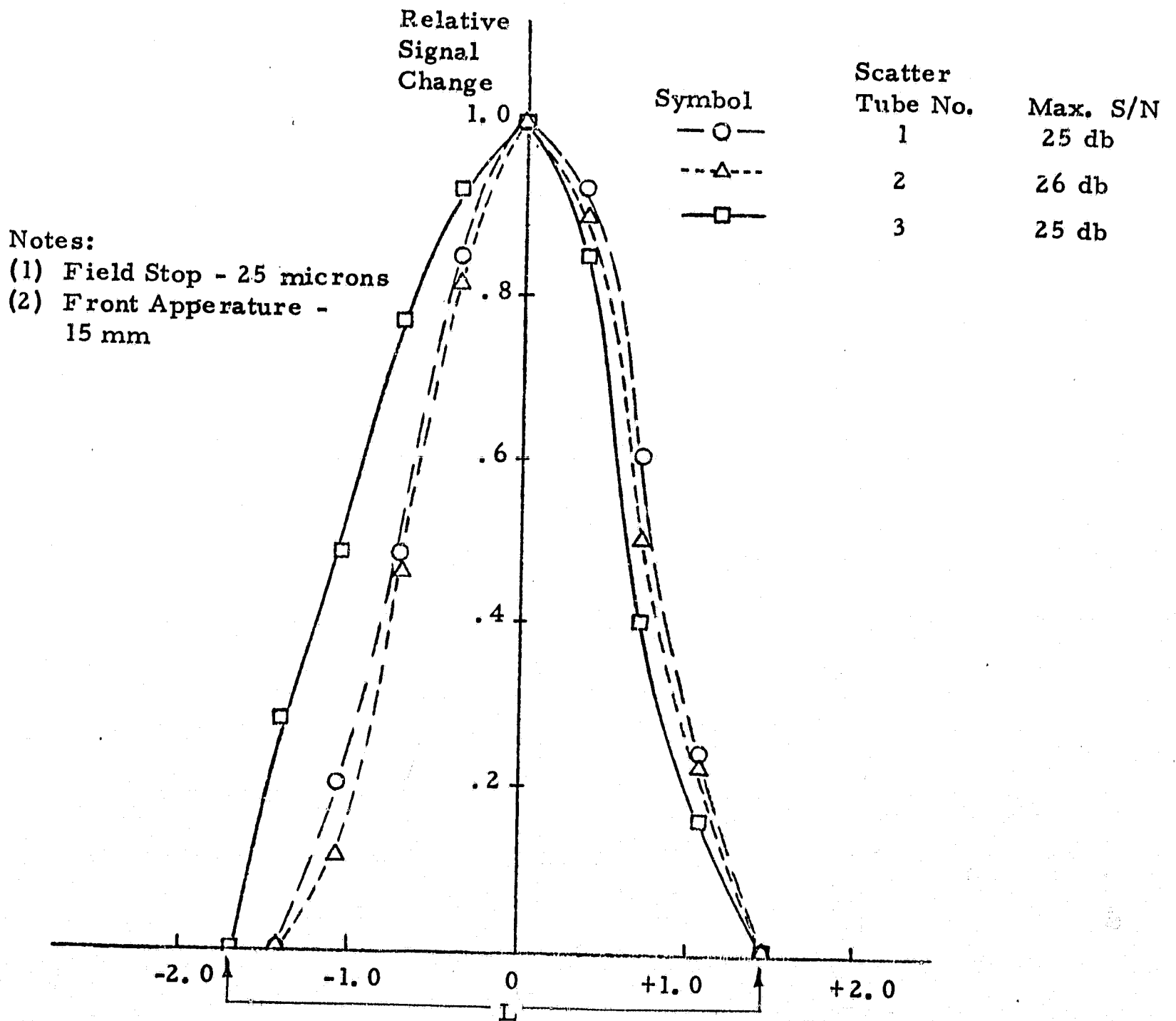
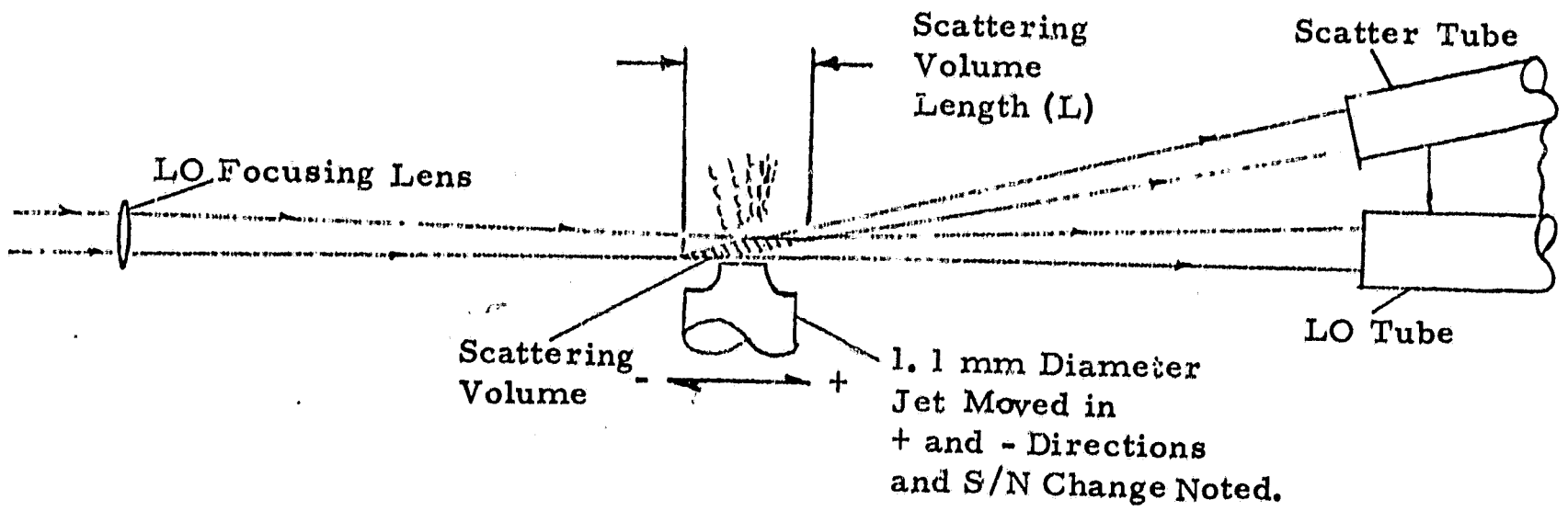


Figure 9. Signal Intensity Variation of the Smallest Scatter Volume Length for the LDV Instrument

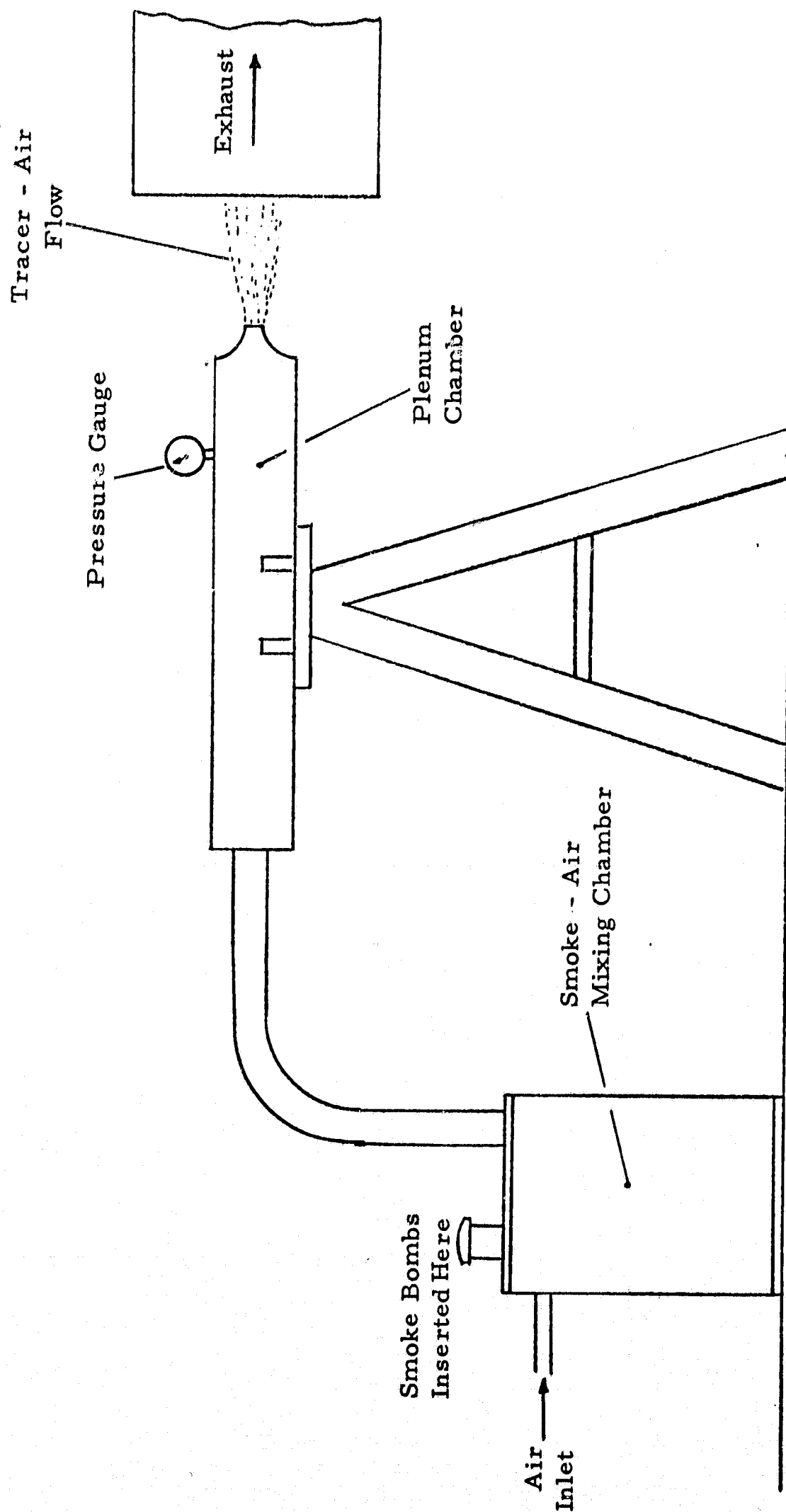


Figure 10. Schematic of the Arrangement for Injection of Smoke Particles into Air Flows.

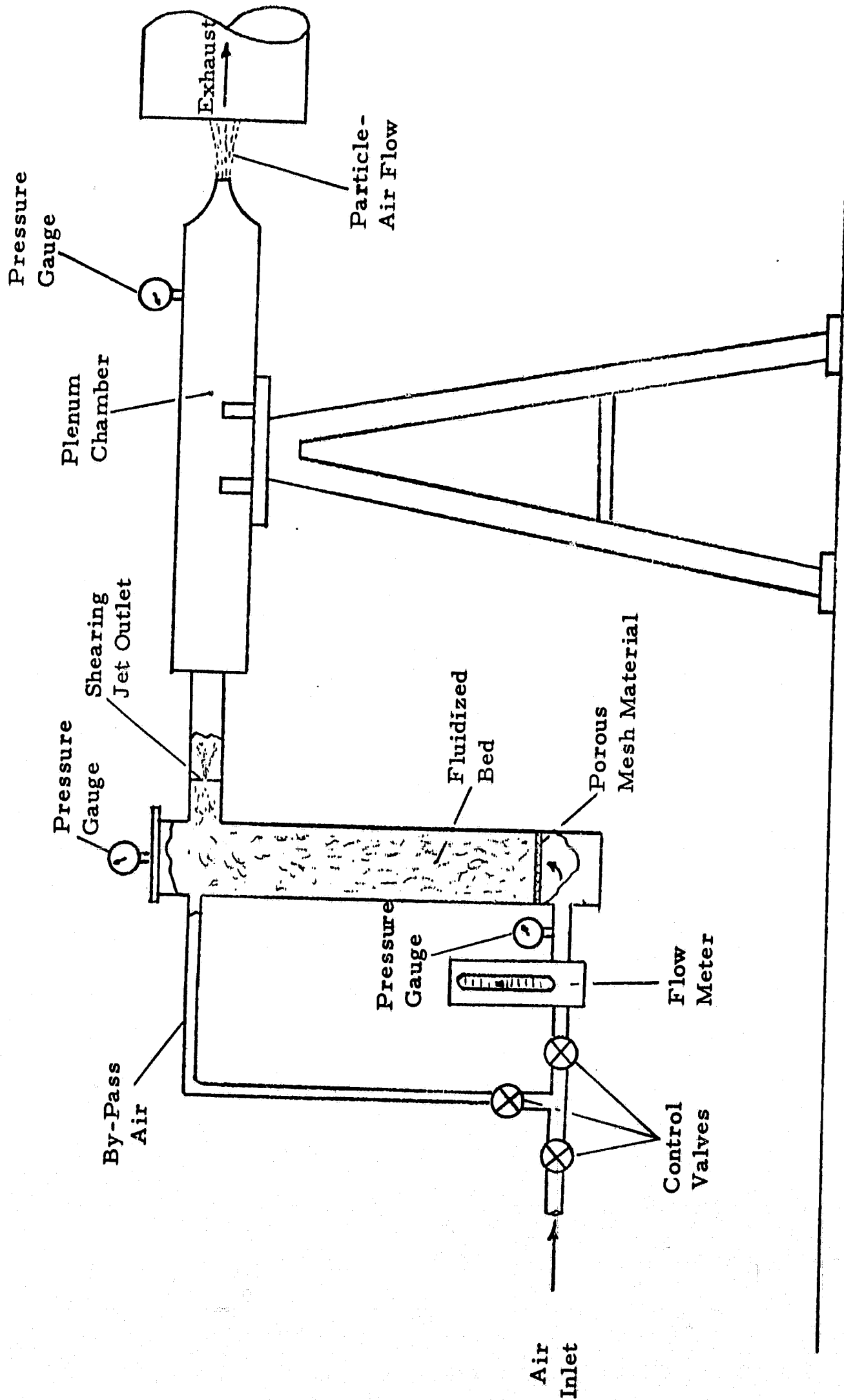
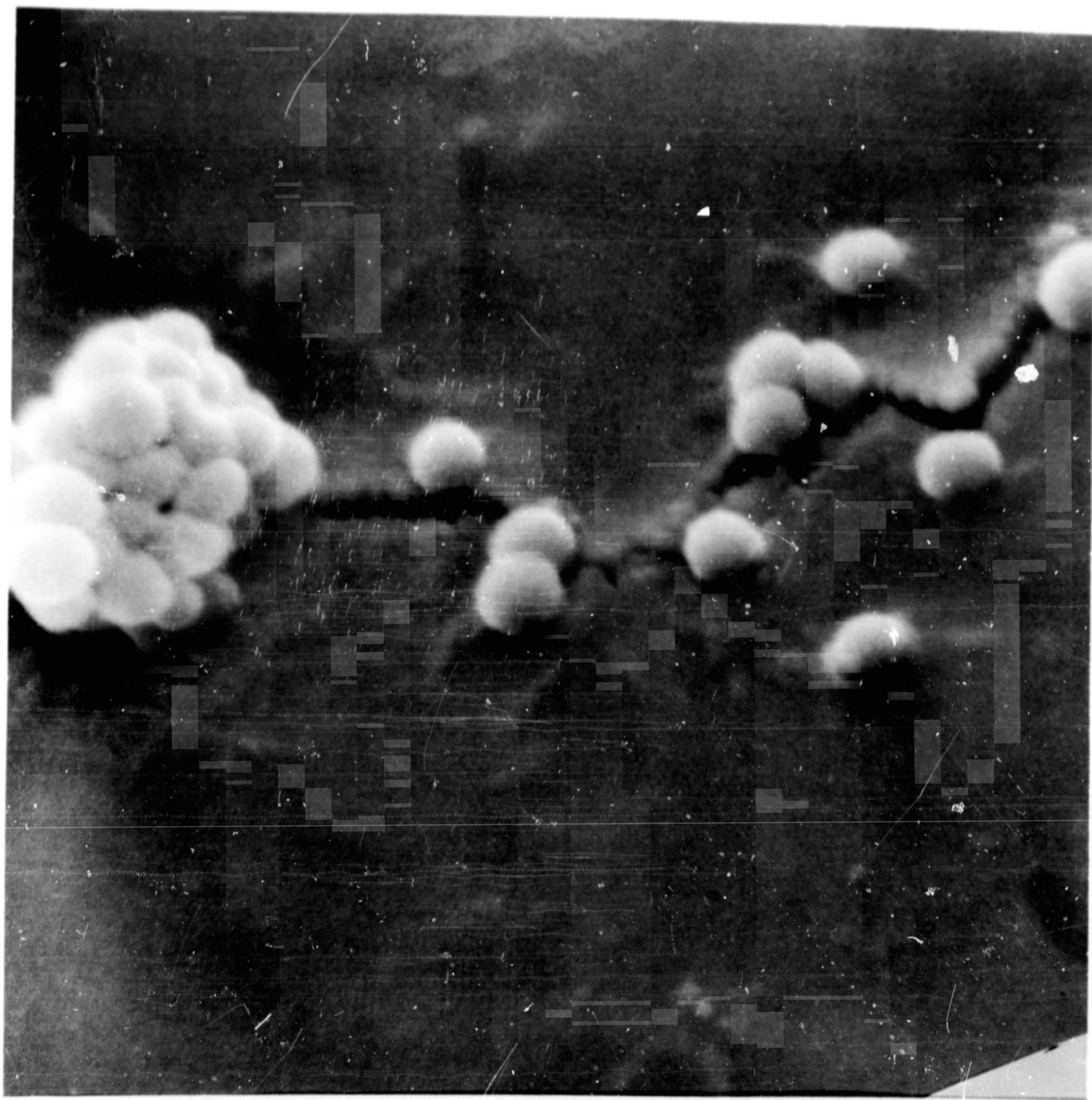


Figure 11. Schematic of the Fluidized Bed Technique for Ejection of Solid Particles into Air Flows.



0.1 μ

Figure 12. Electron Photomicrograph of Polyvinyl
Chloride Material (Geon 126) at a
Magnification of 46,640x

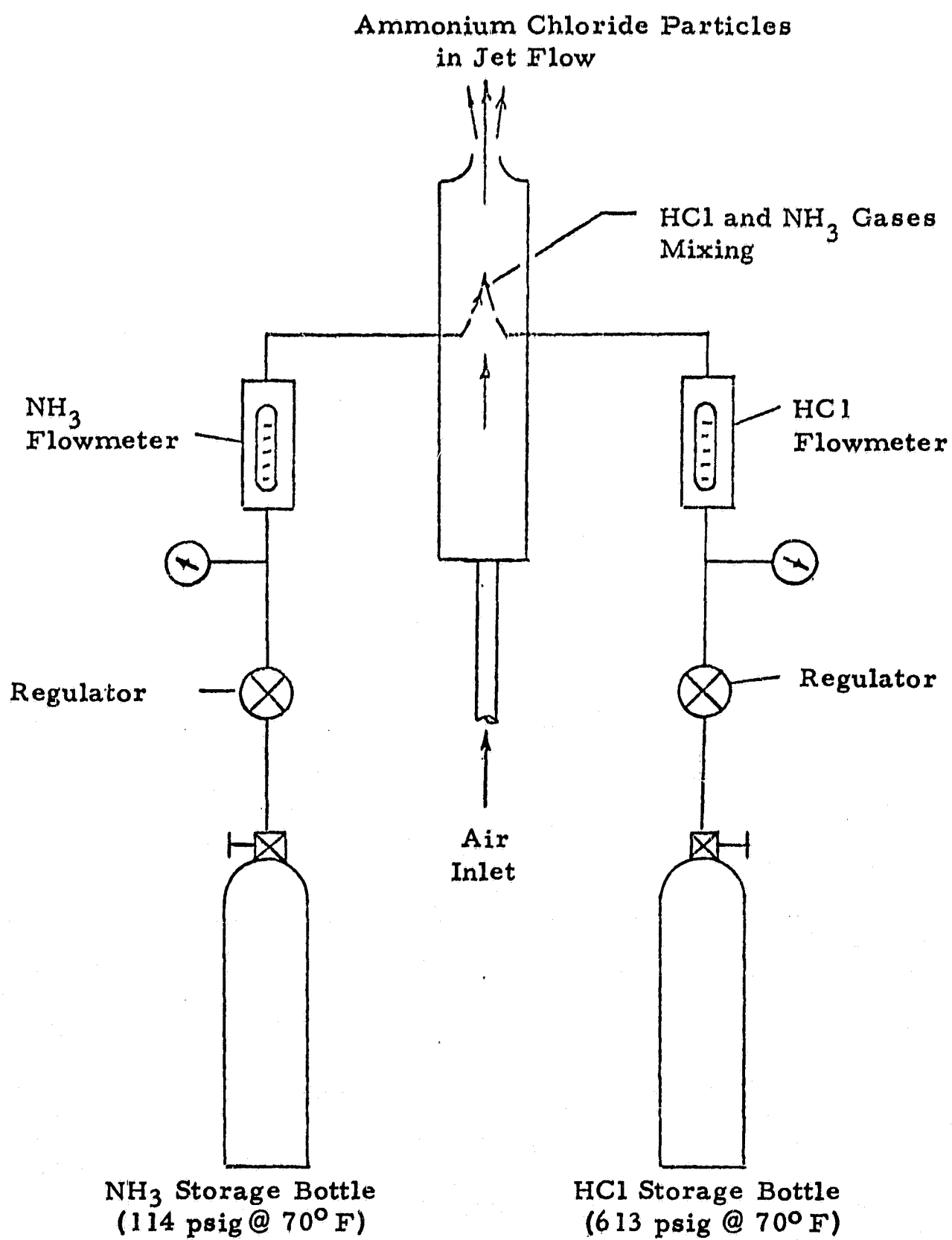


Figure 13. Schematic of Ammonia and Hydrogen Chloride Gas Mixing System for Producing Ammonium Chloride Tracer Particles

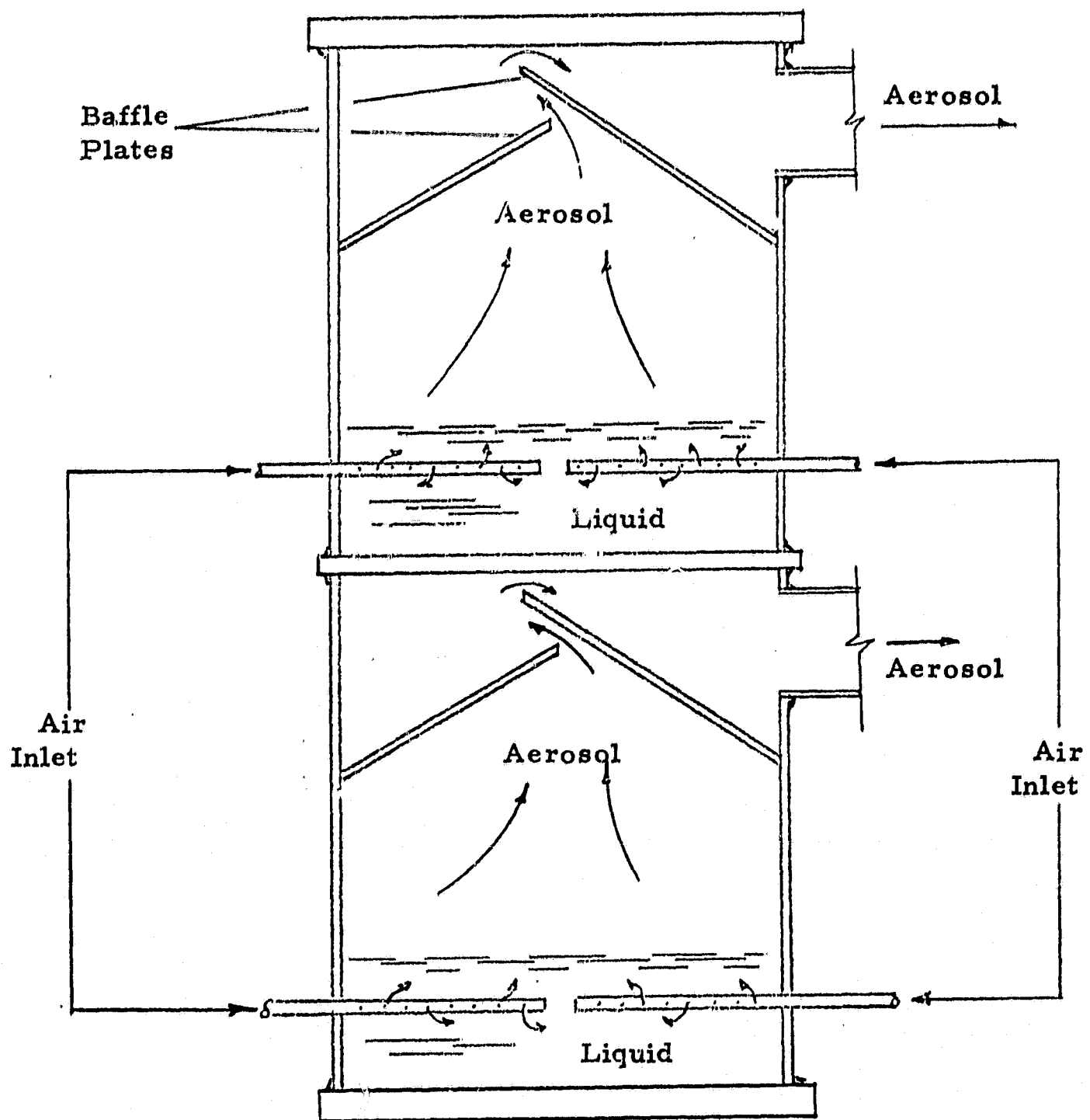


Figure 14. Schematic of Two Stage Shearing Jet Aerosol Generator

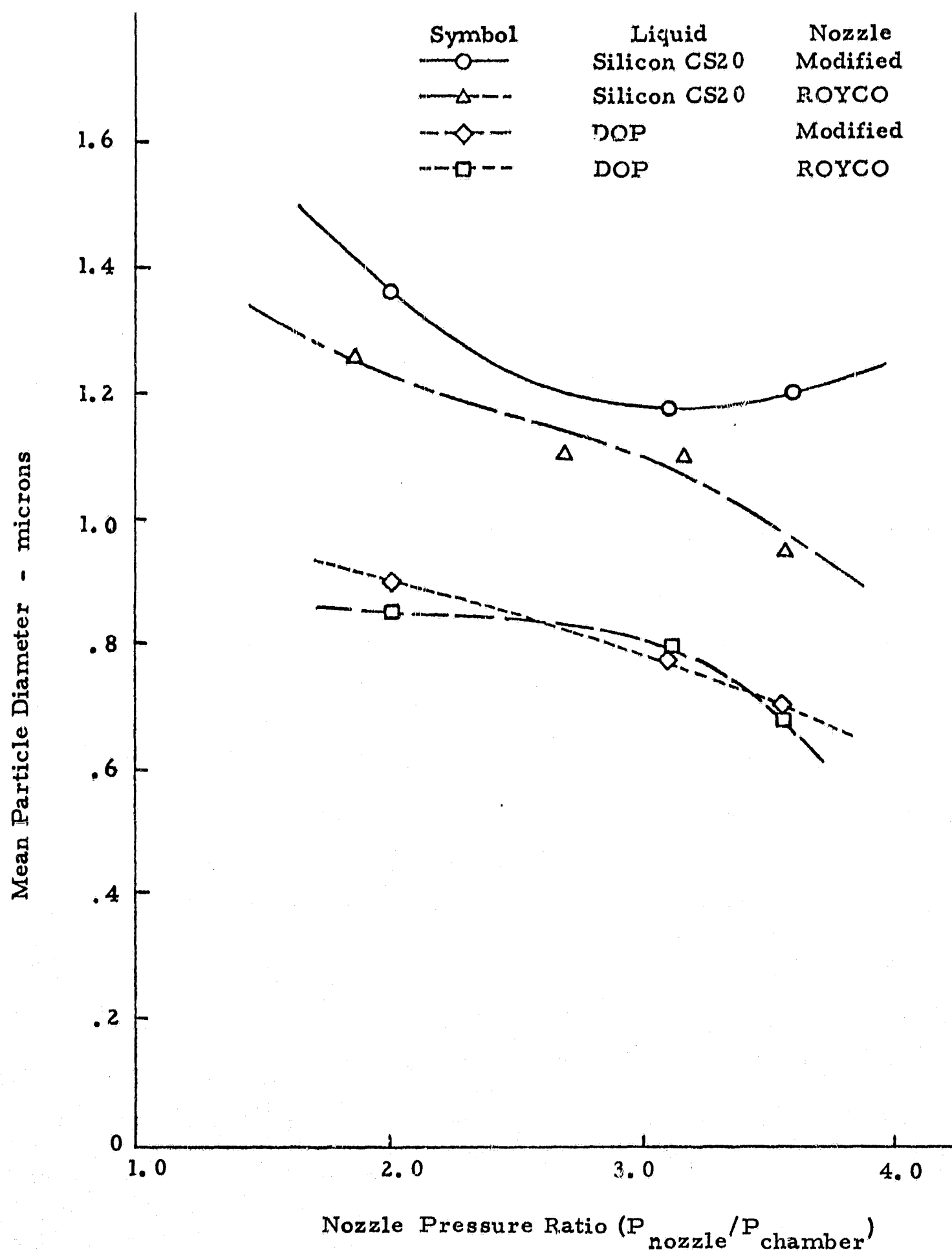


Figure 15. Mean Mass Particle Diameters Produced by a ROYCO and Modified Nozzles for Different Operating Pressures and Liquids

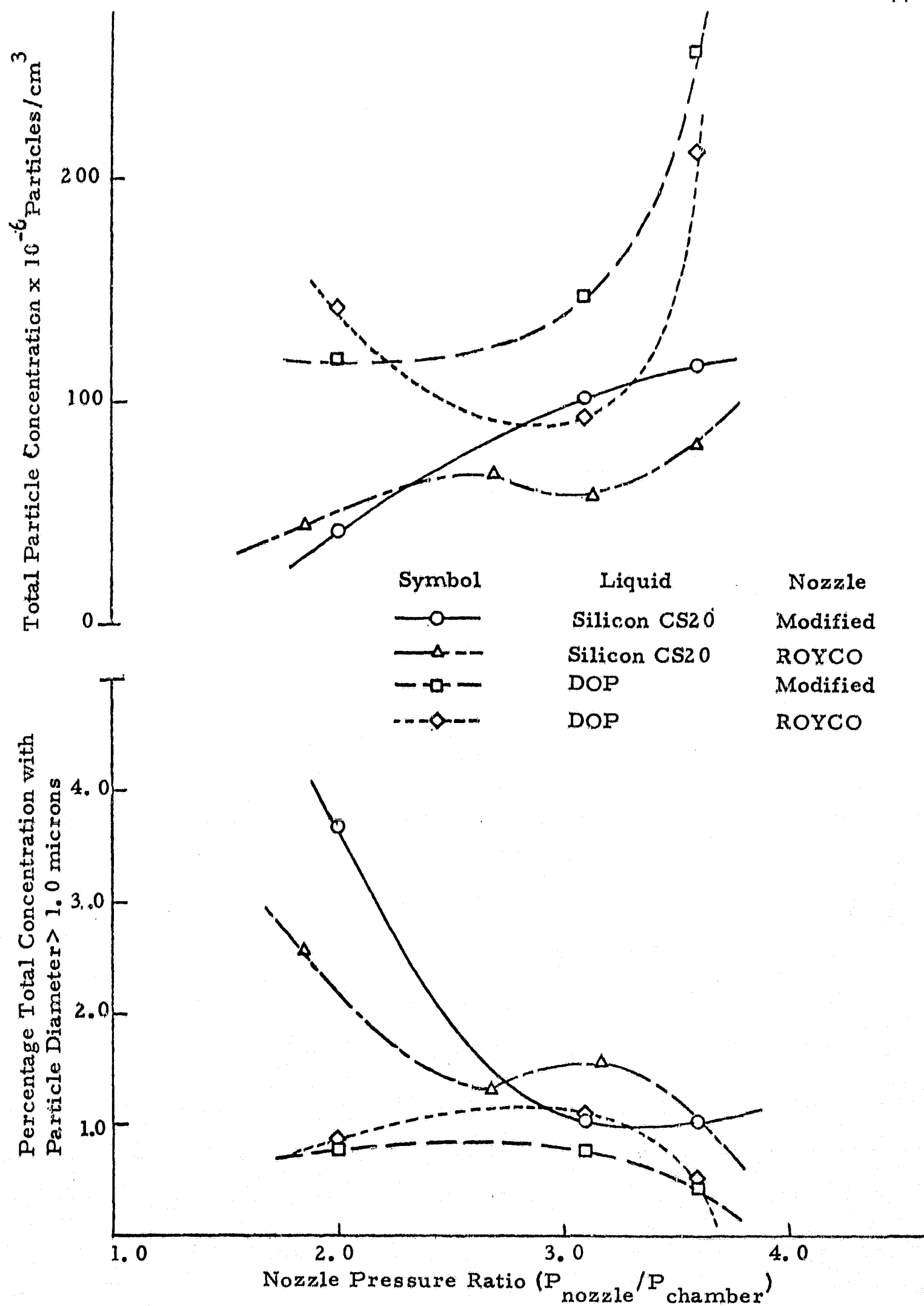


Figure 16. Aerosol Particle Concentrations Produced by a ROYCO and Modified Nozzles for Different Operating Pressures and Liquids

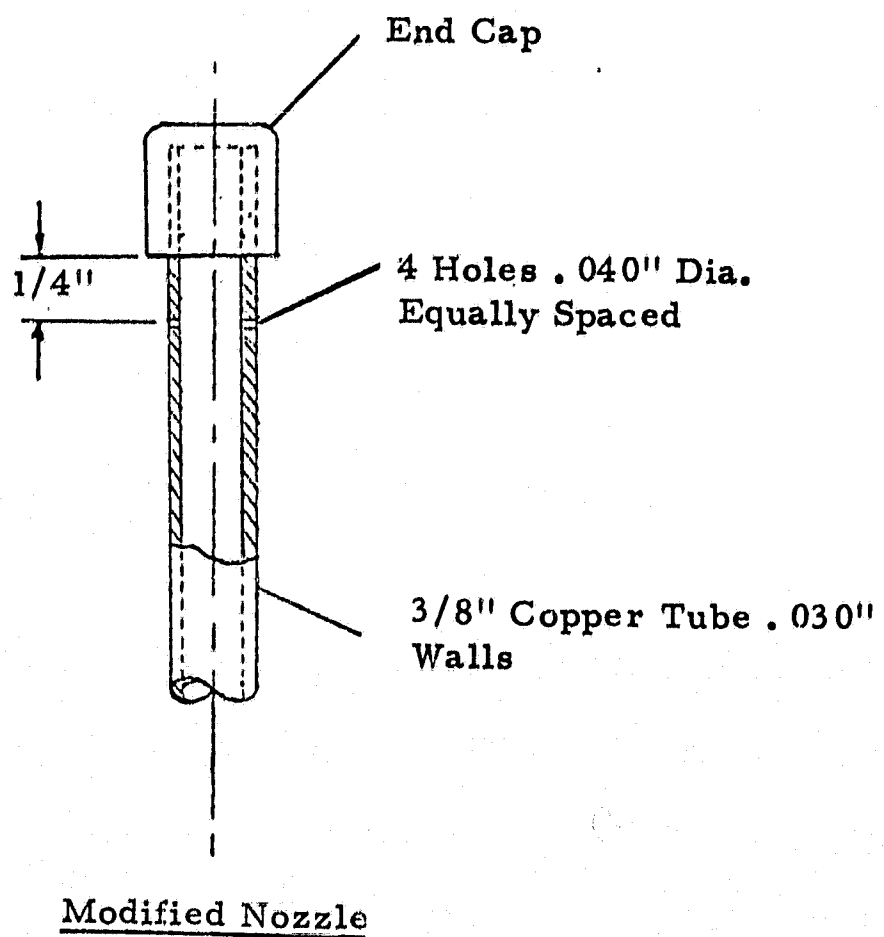
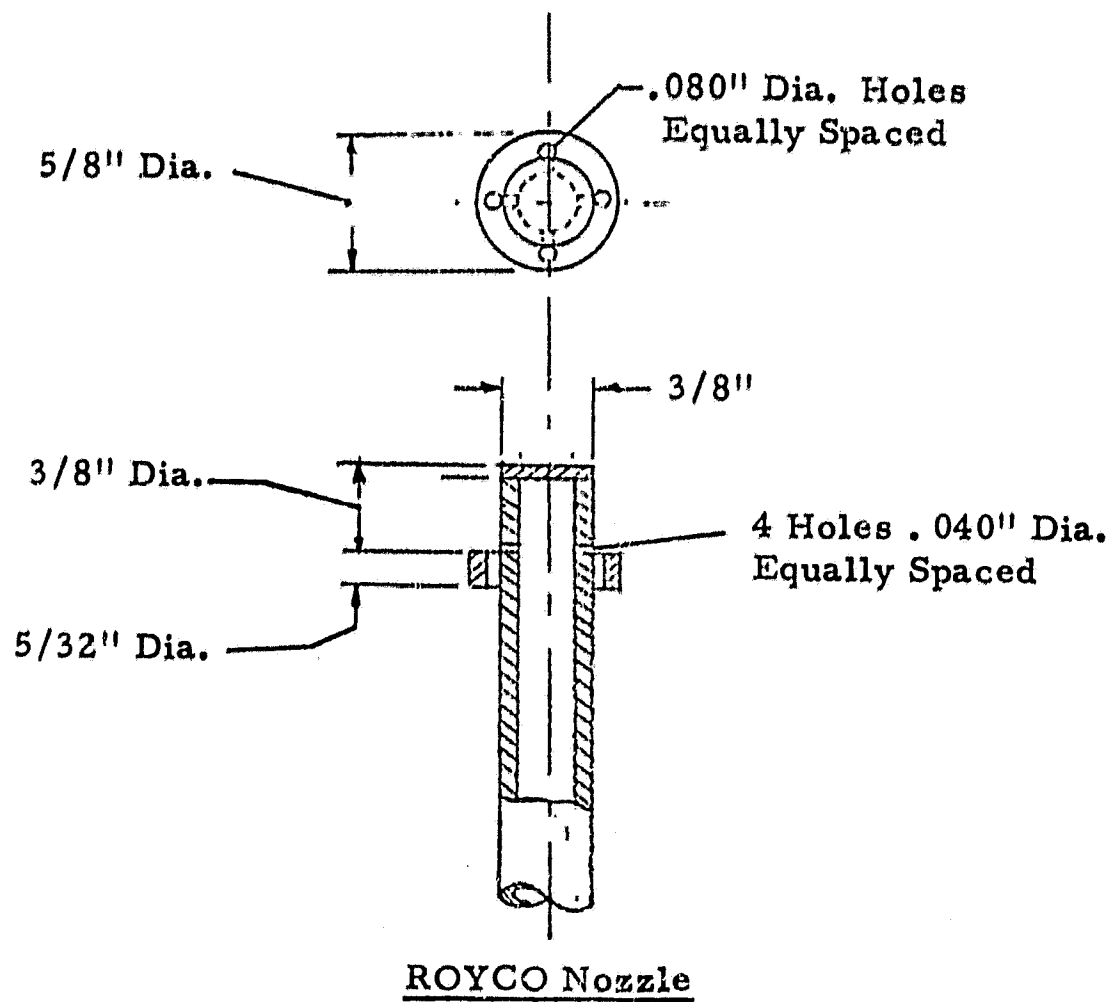


Figure 17. ROYCO and Modified Nozzle Configuration Used in ROYCO Aerosol Generator

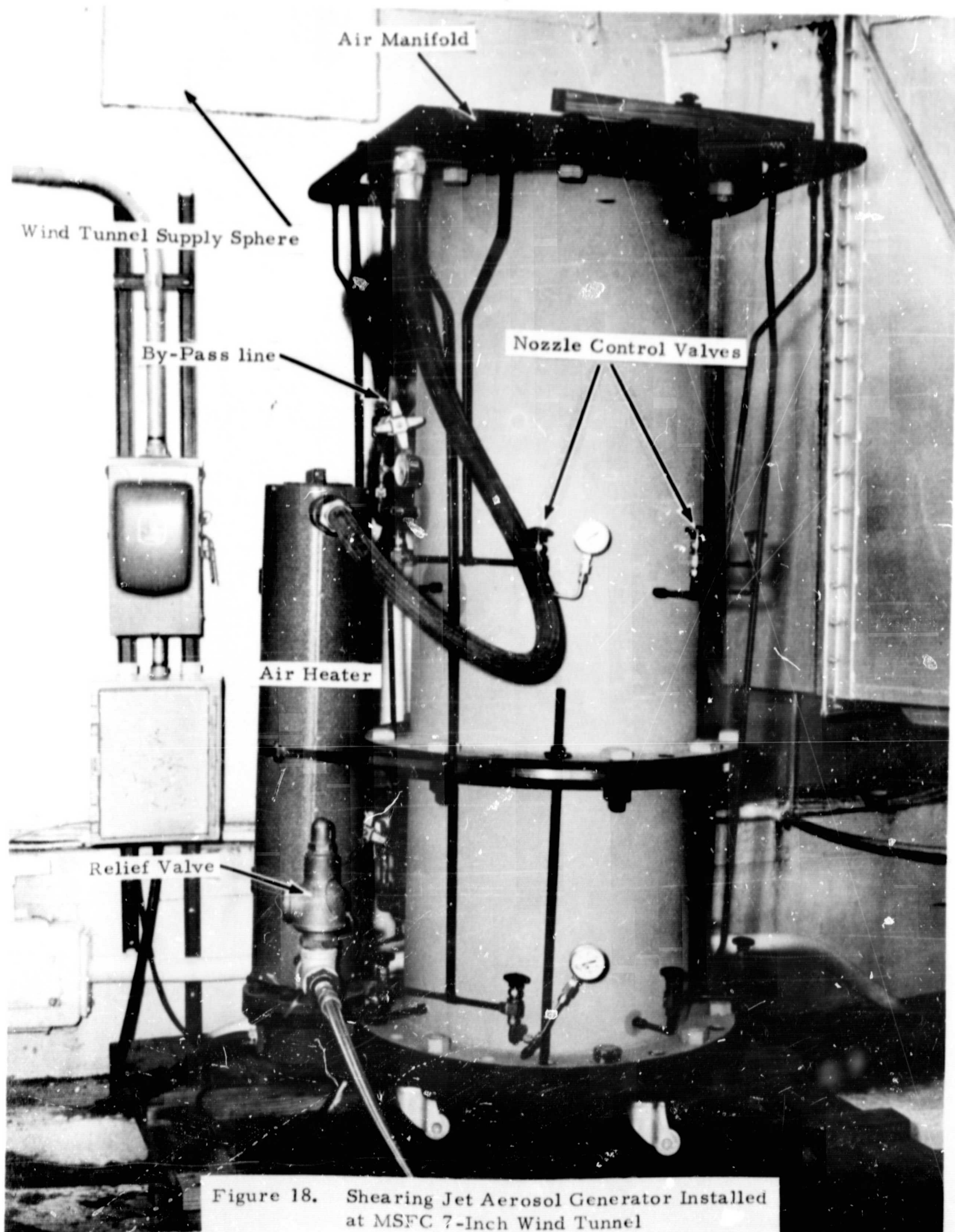


Figure 18. Shearing Jet Aerosol Generator Installed at MSFC 7-Inch Wind Tunnel

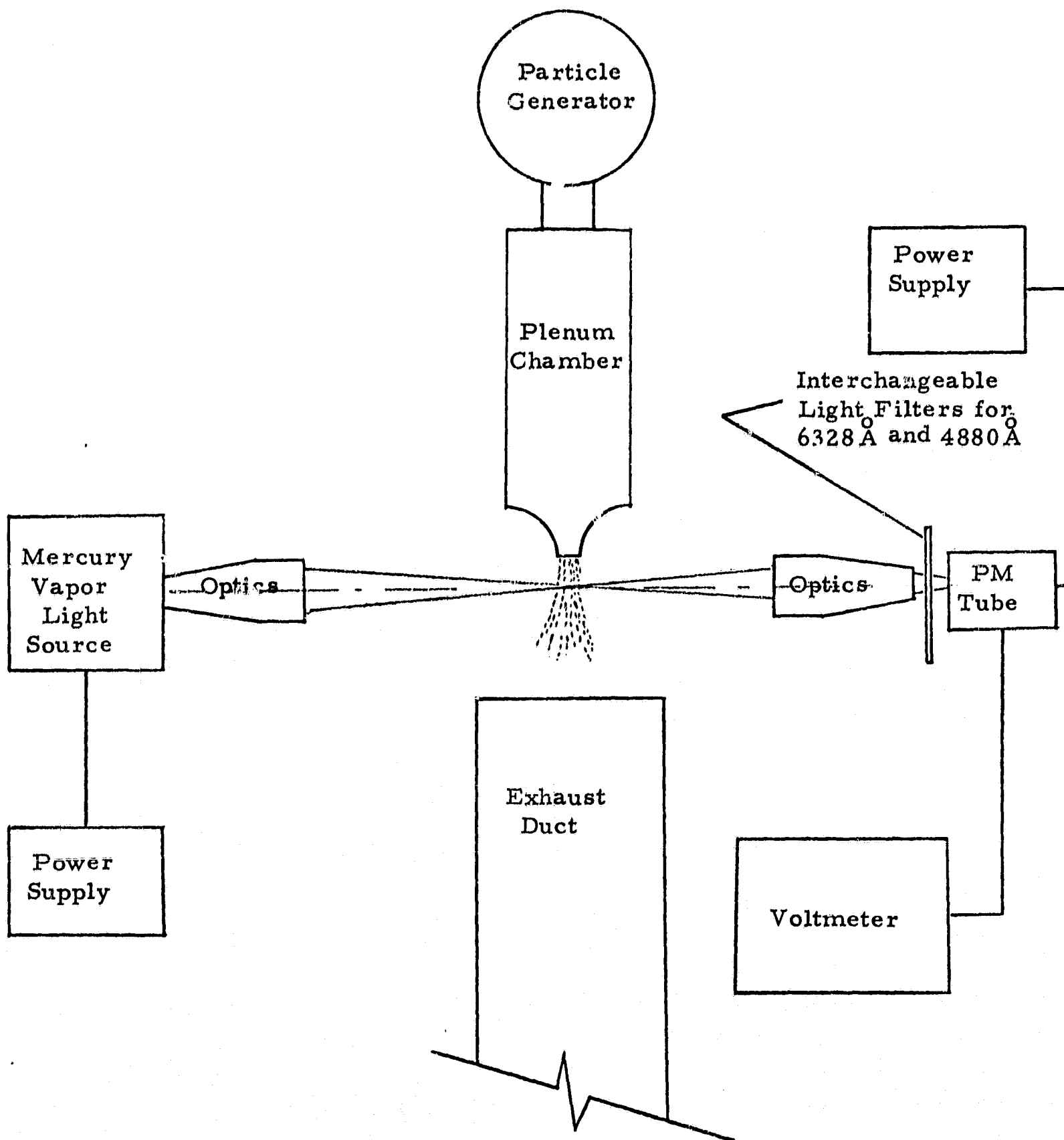


Figure 19. Schematic Diagram of System for Measuring Mean Particle Size and Concentration With a Light Scattering and Transmission Technique

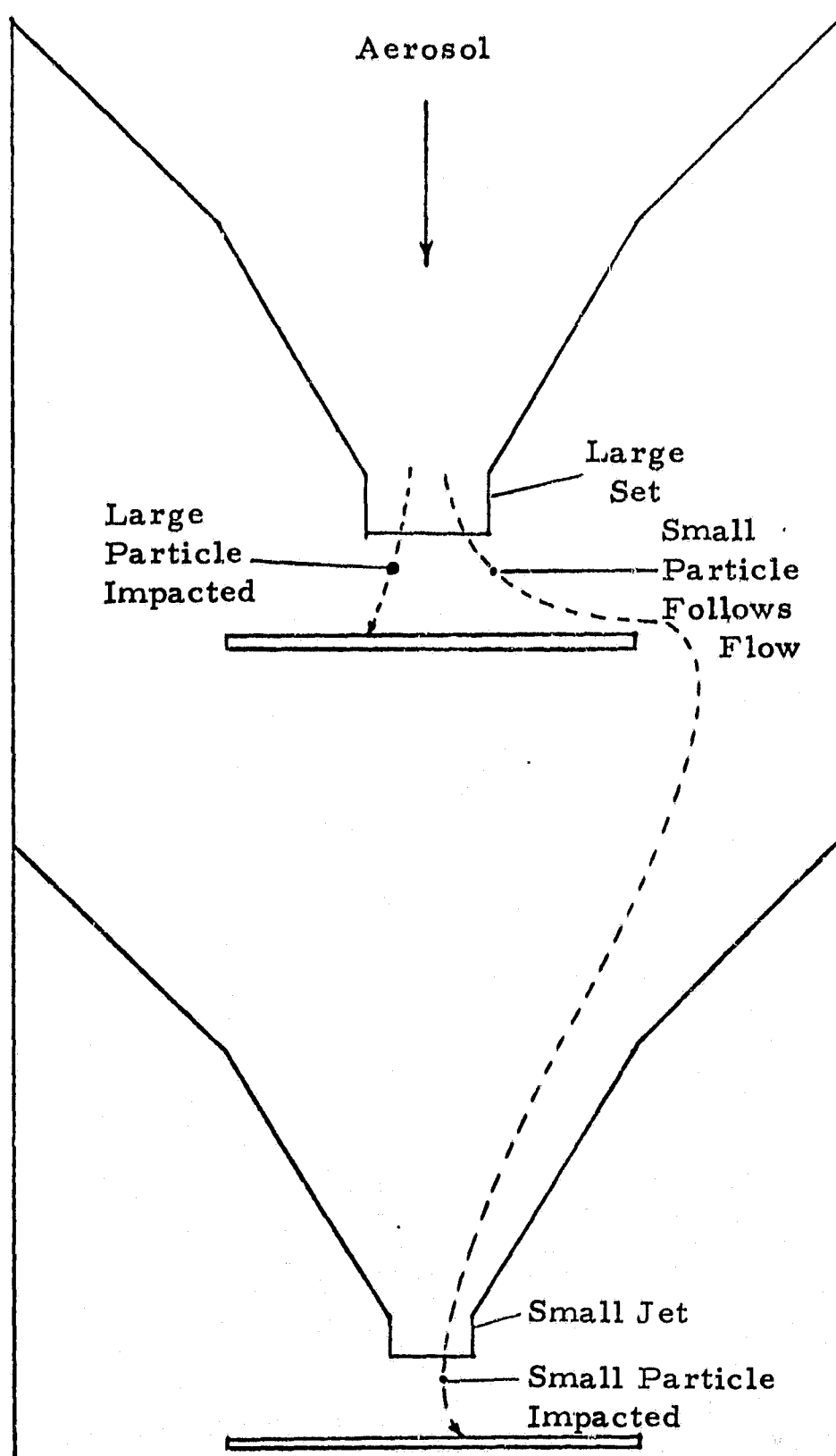


Figure 20. Schematic Diagram Showing Principle of the Cascade Impactor.

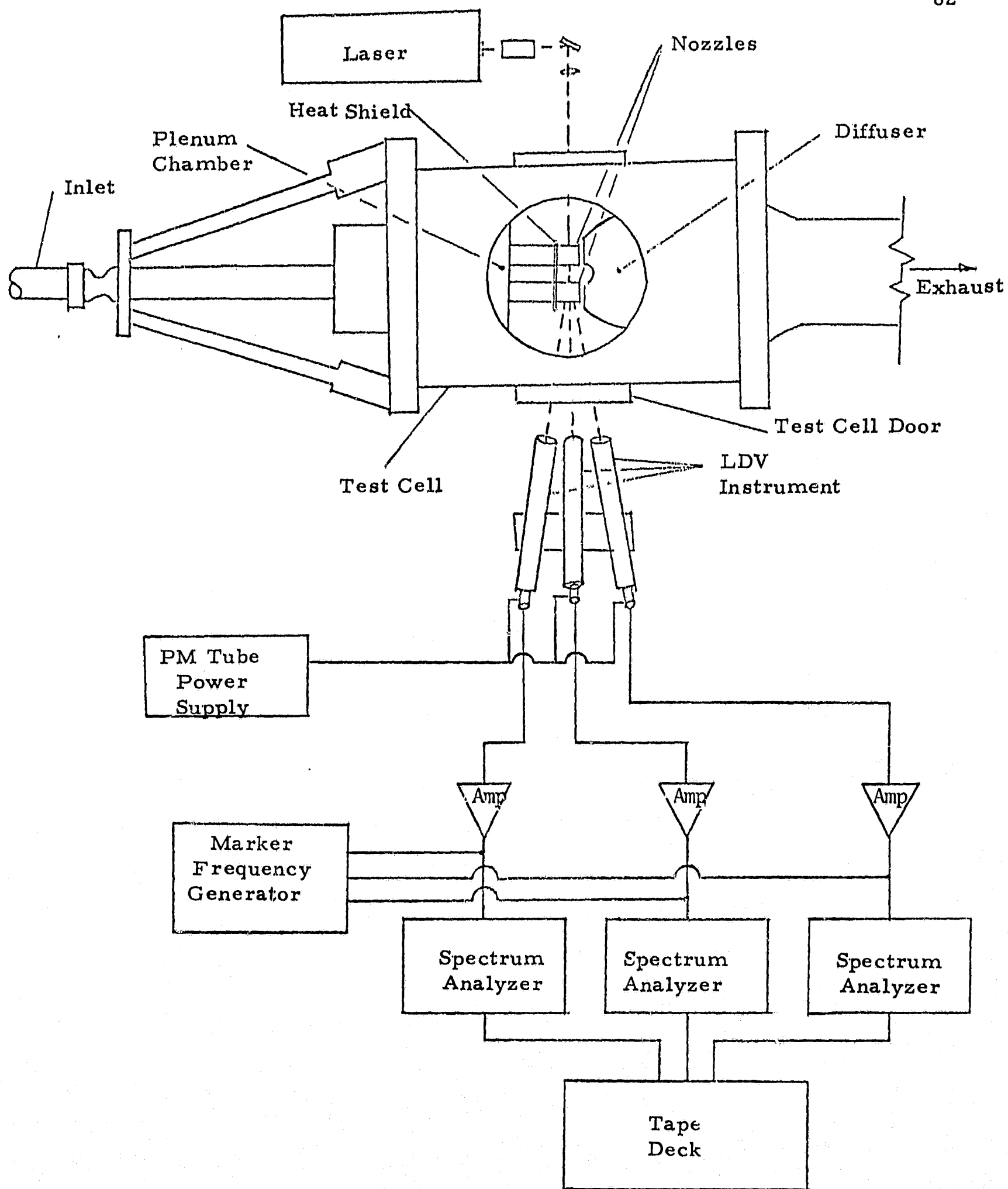


Figure 21. Test Cell and LDV System Arrangement for AEDC Base Flow Measurements

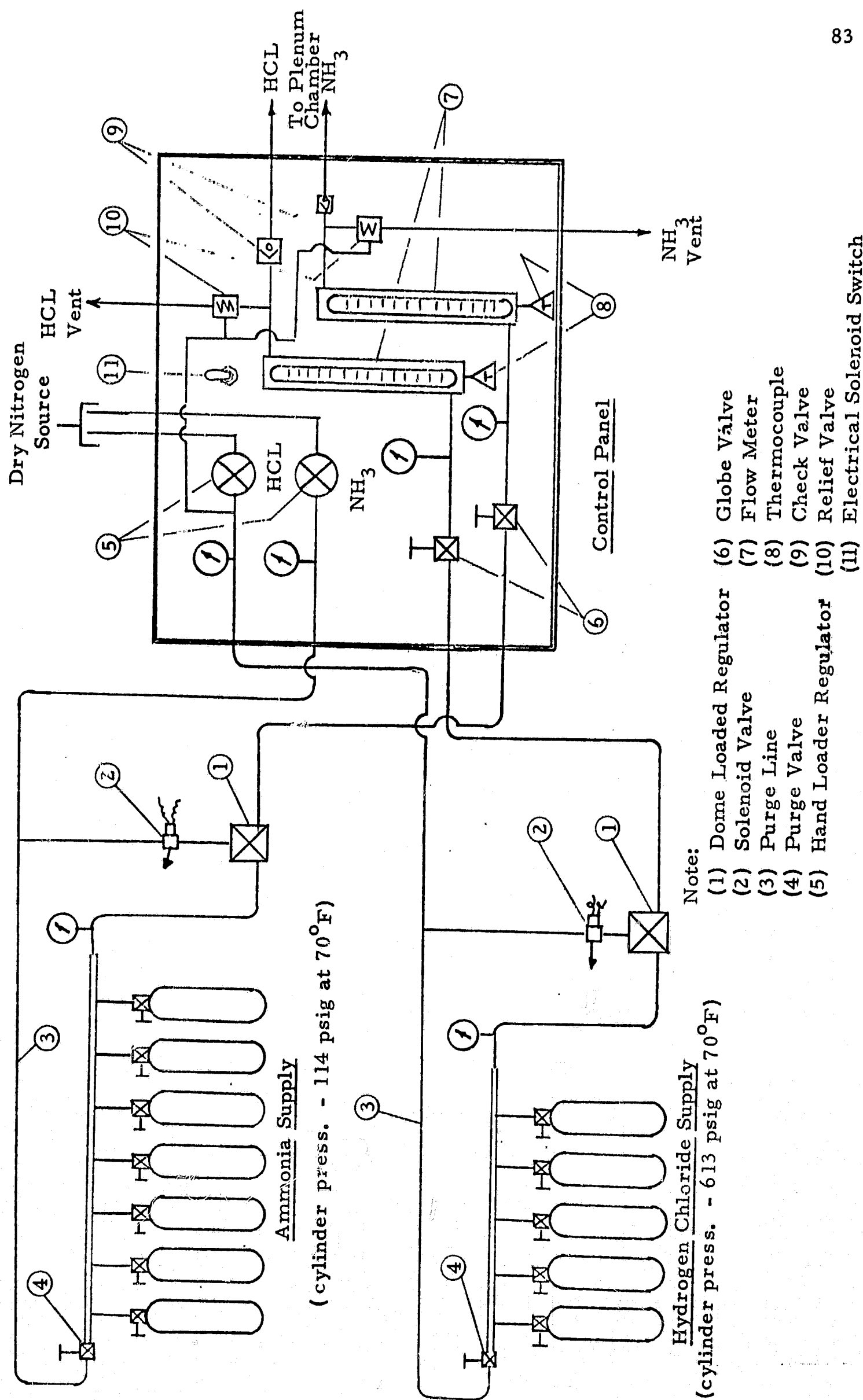


Figure 22. Ammonia and Hydrogen Chloride Gas Control System for Tracer System at AEDC Base Flow Tests

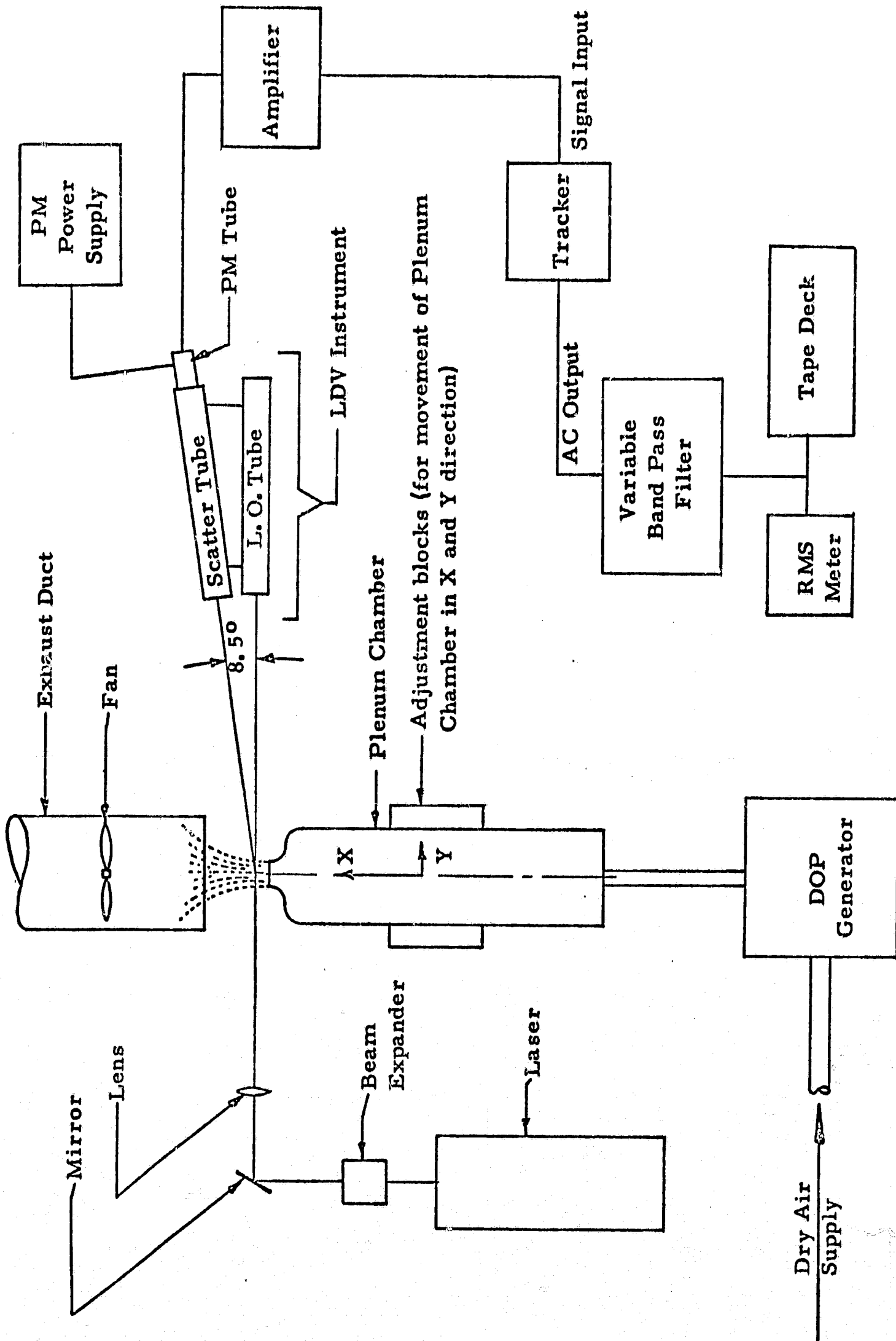


Figure 23. Schematic Diagram of LDV System Arrangement for Subsonic Free Jet Turbulence Measurements

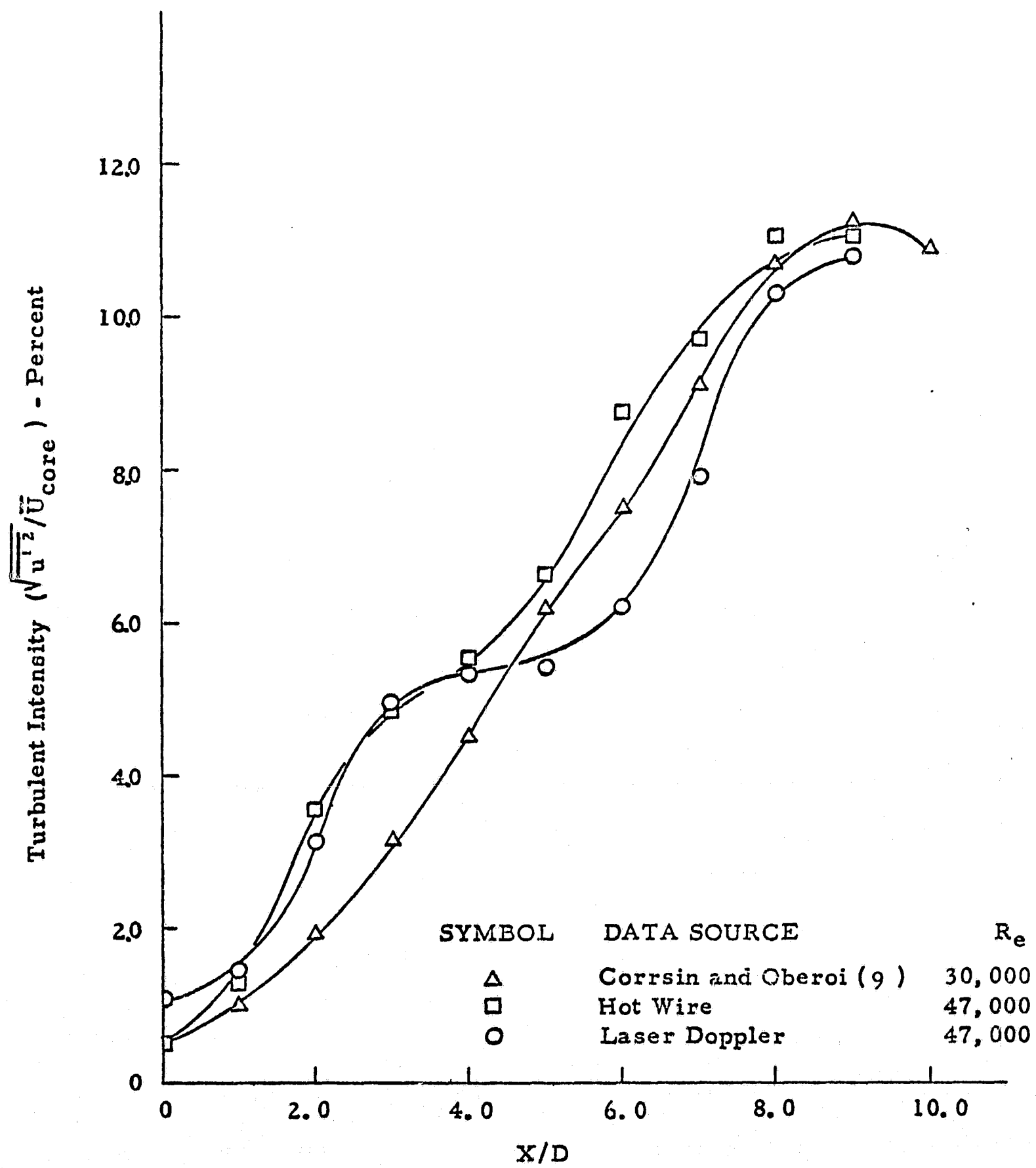


Figure 24. Distribution of Turbulence Intensity Along the Axis of a Round Free Jet

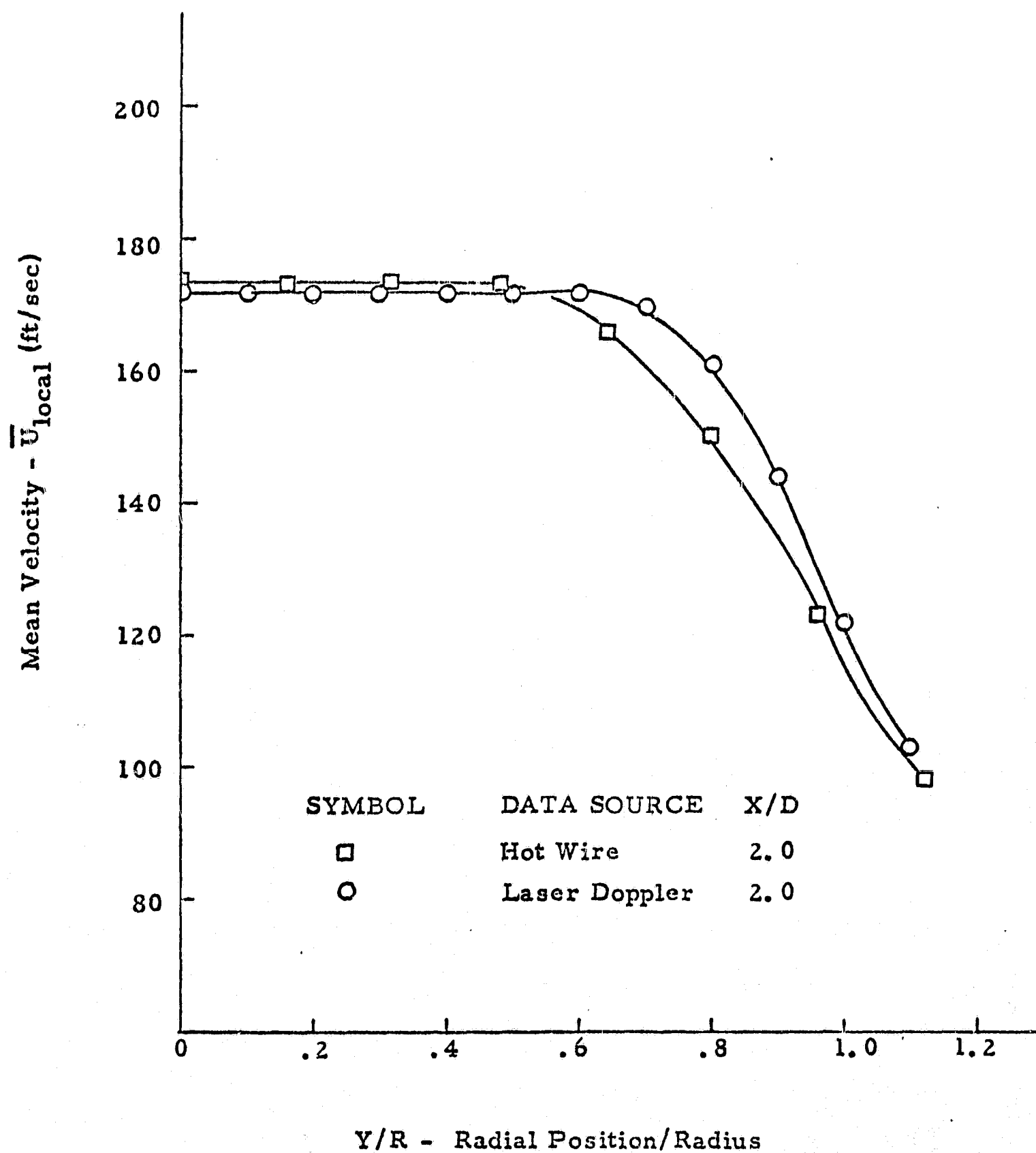


Figure 25. Comparison of Mean Velocity Profile for a Round Free Jet

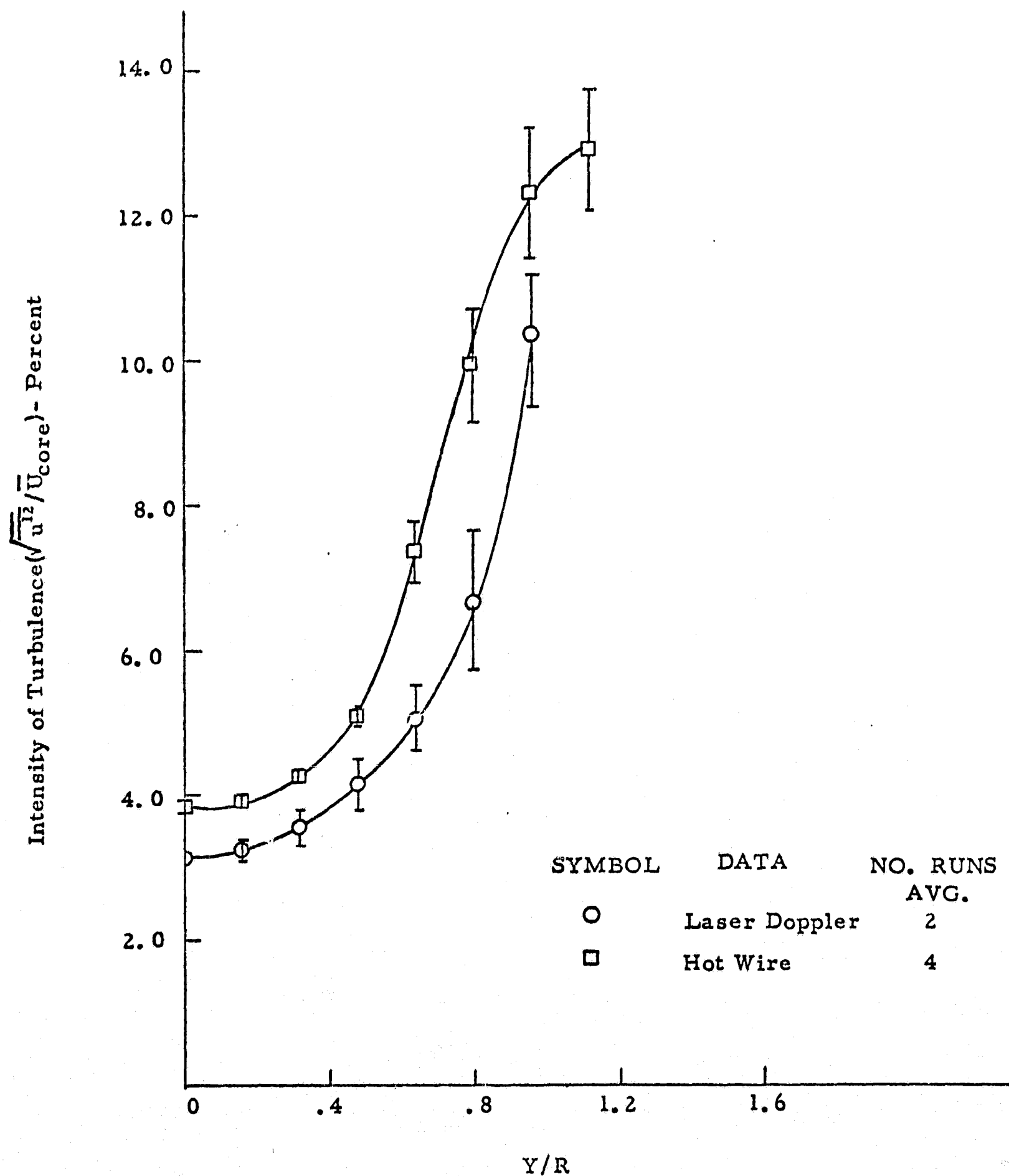


Figure 26. Comparison of Turbulent Intensity Profile for a Round Free Jet

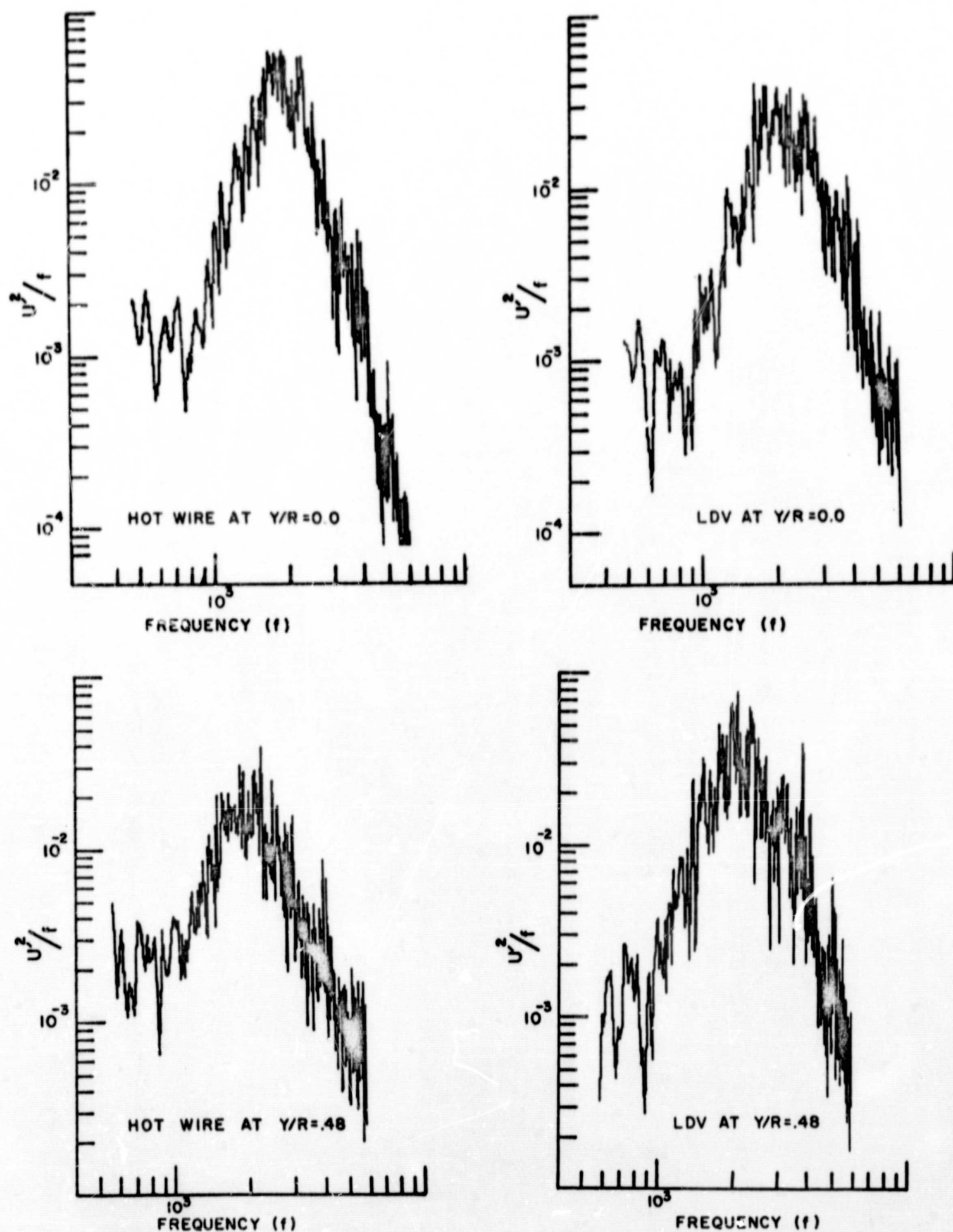


Figure 27. Comparisons of LDV and Hot Wire Spectral Distribution for a 0.5 Inch Diameter Jet With Core Velocity of 173 f/s ($x/D = 2.0$)

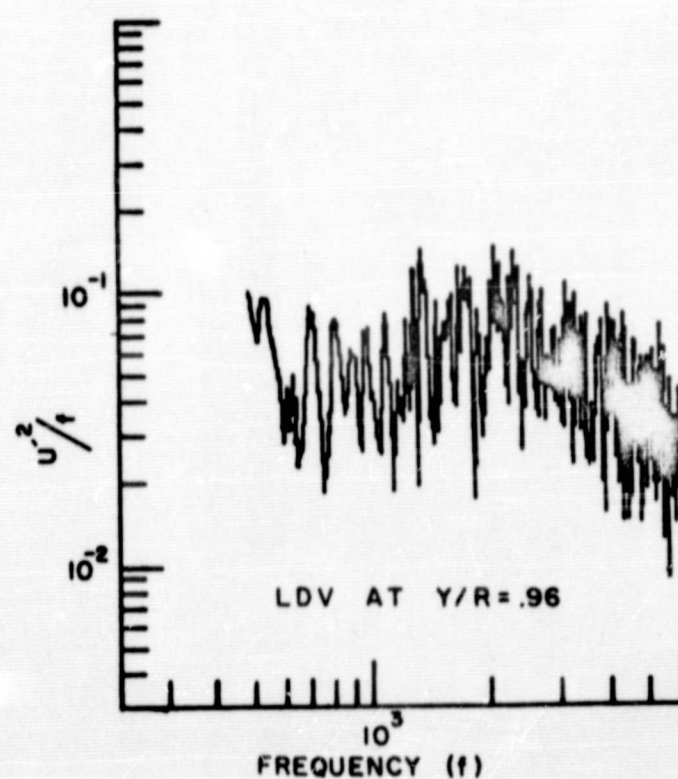
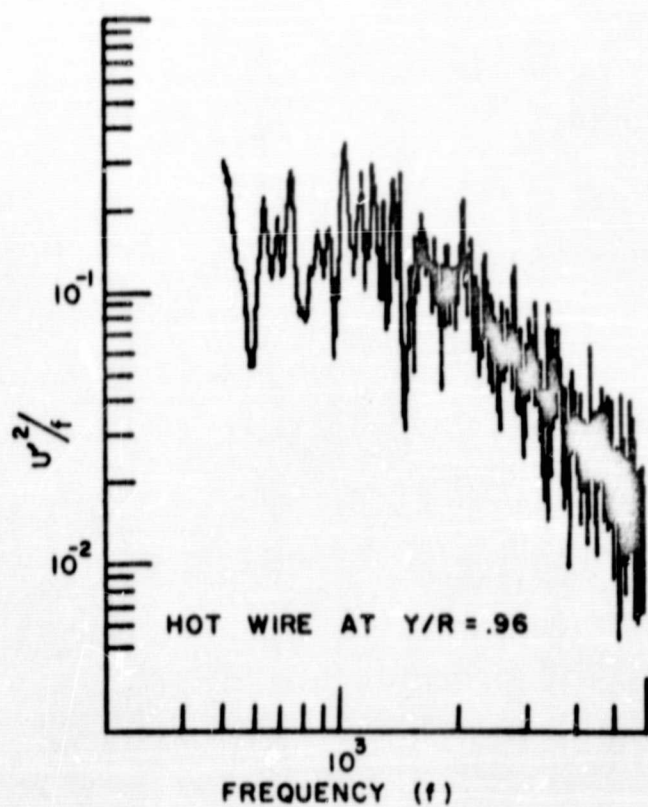
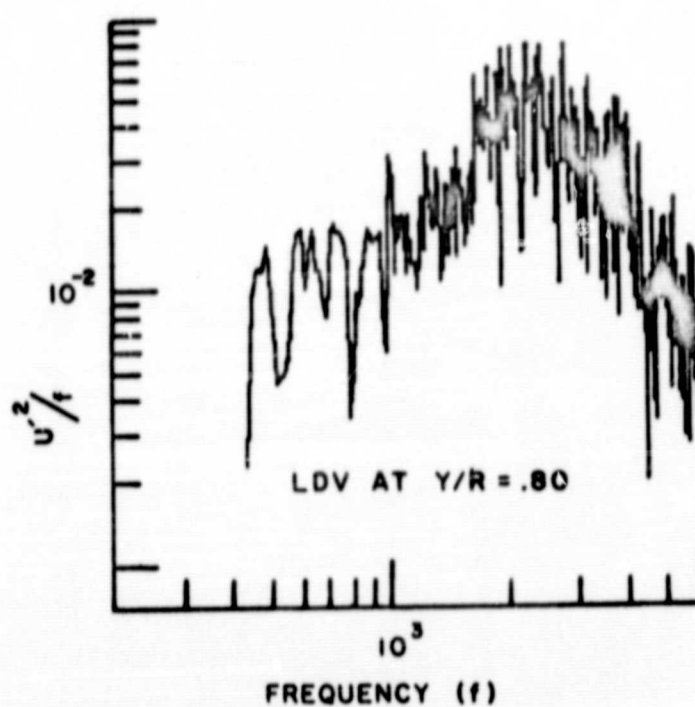
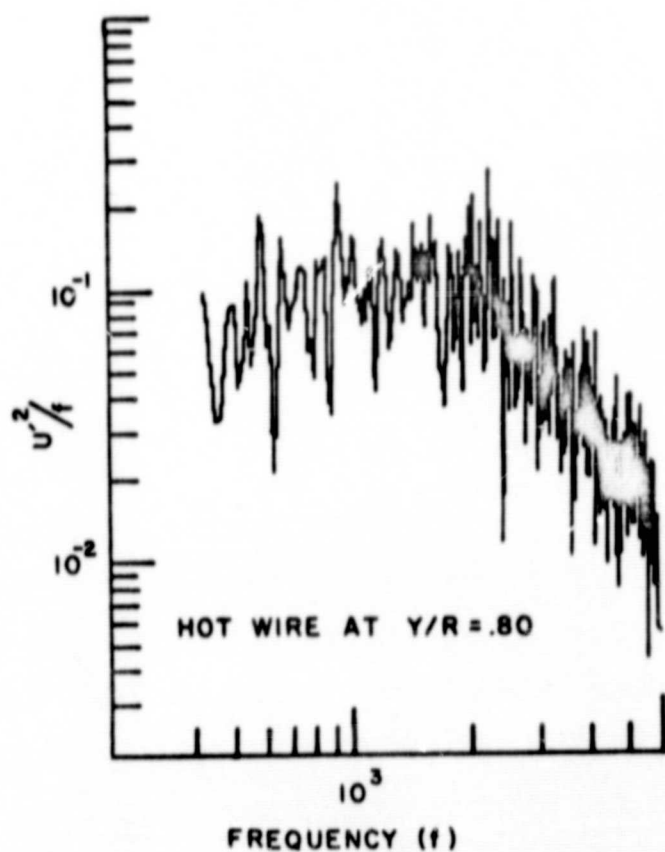


Figure 28. Comparisons of LDV and Hot Wire Spectral Distributions for a 0.5 Inch Diameter Jet With Core Velocity of 173 f/s ($x/D = 2.0$)

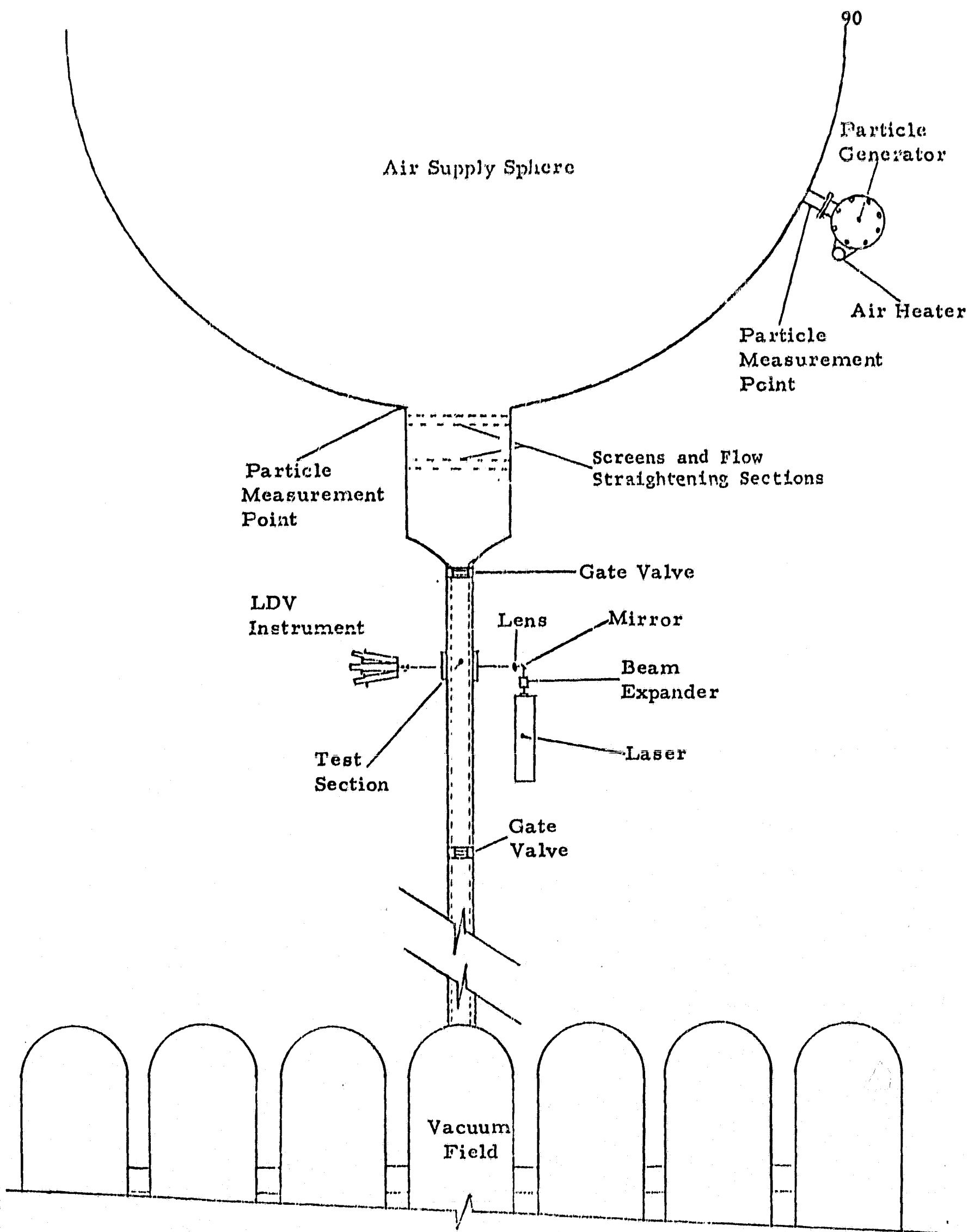


Figure 29. MSFC 7-Inch Wind Tunnel Layout for LDV Tests

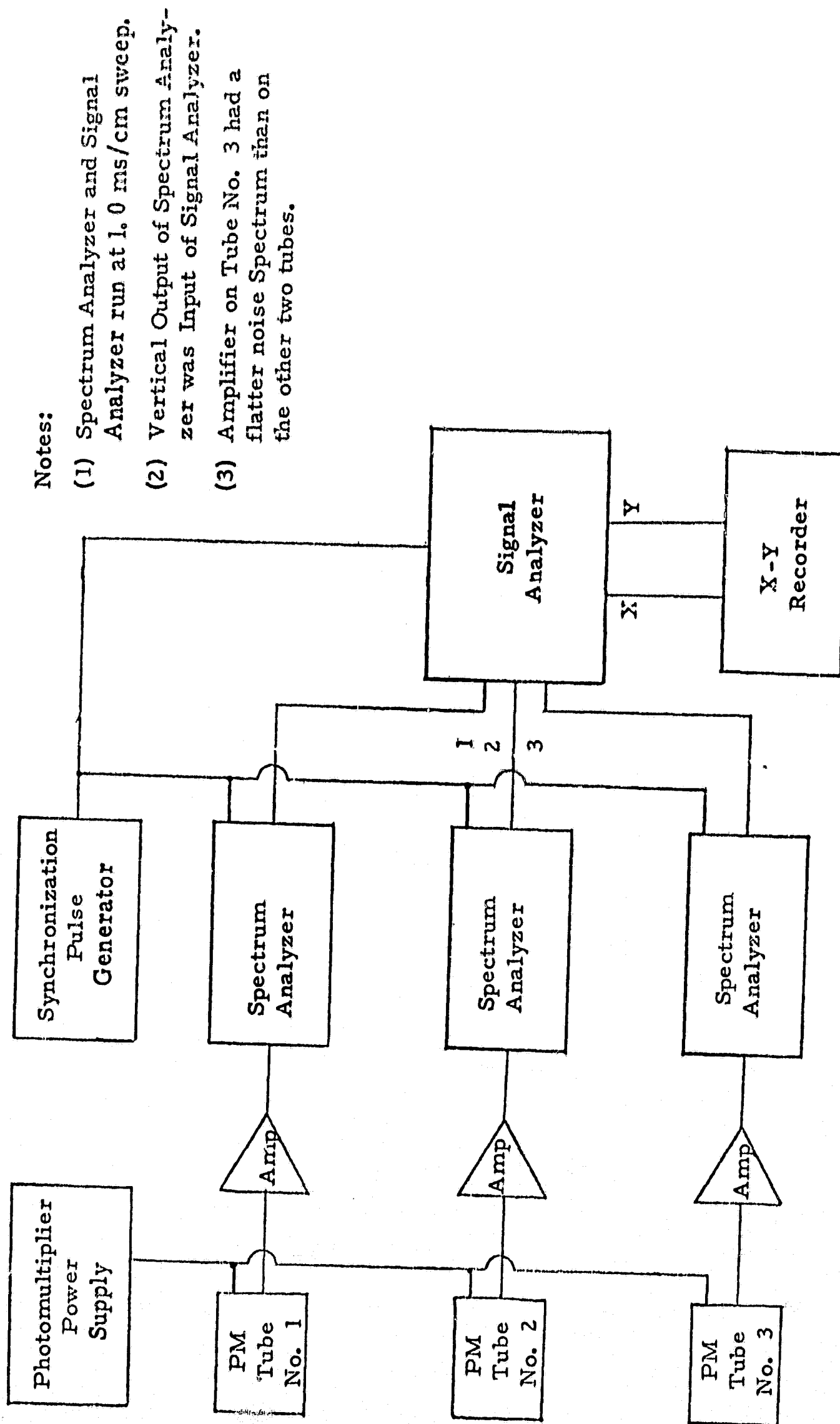


Figure 30. Schematic of Electronic Network for Data Acquisition at the 7-Inch Wind Tunnel Tests.

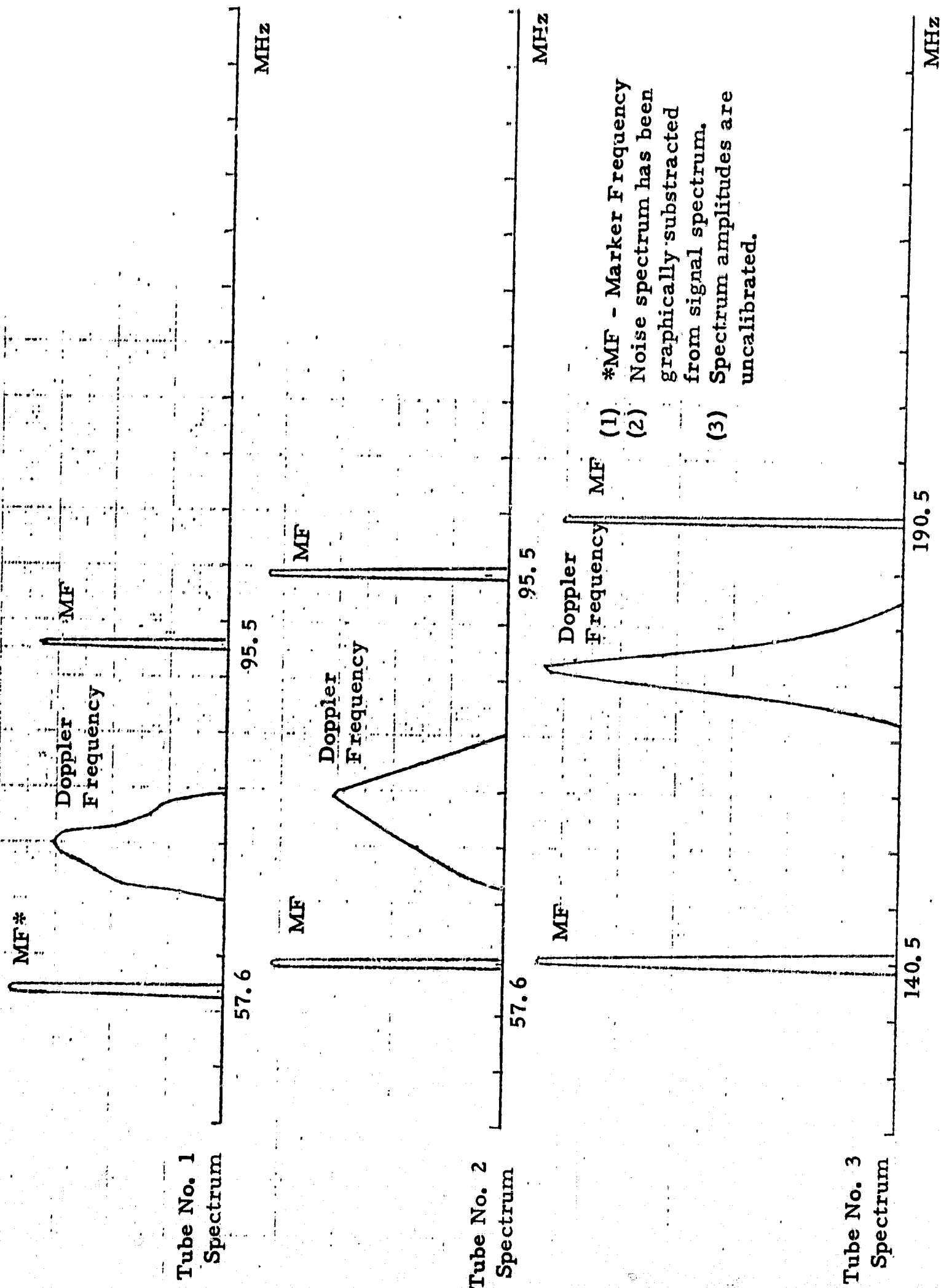


Figure 31. Typical Doppler Frequency Spectrums for 7-Inch Wind Tunnel Test

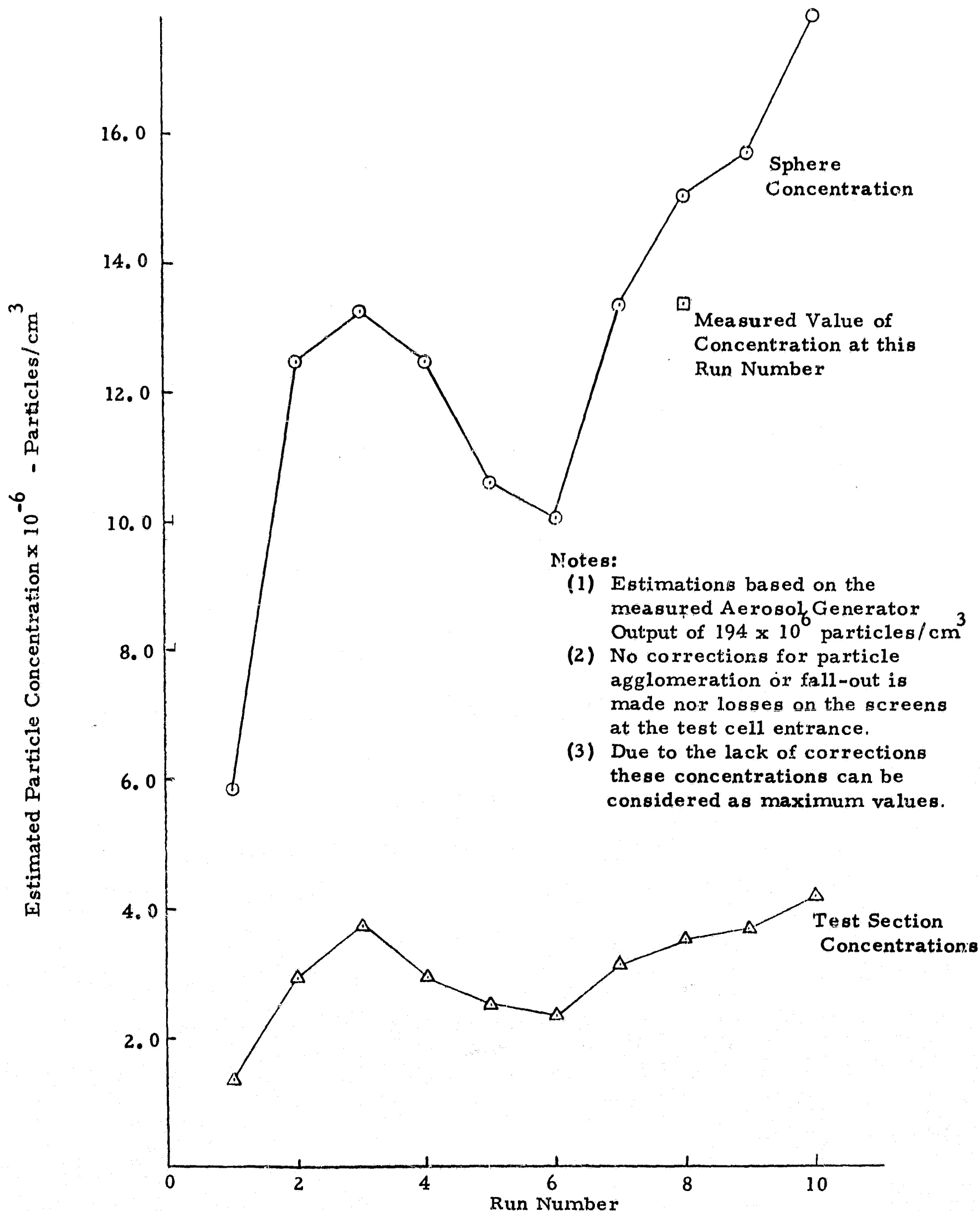


Figure 32. Estimation of Reservoir Sphere and Test Section Particle Concentrations For a Typical Series of Runs at the 7-Inch Wind Tunnel Facility

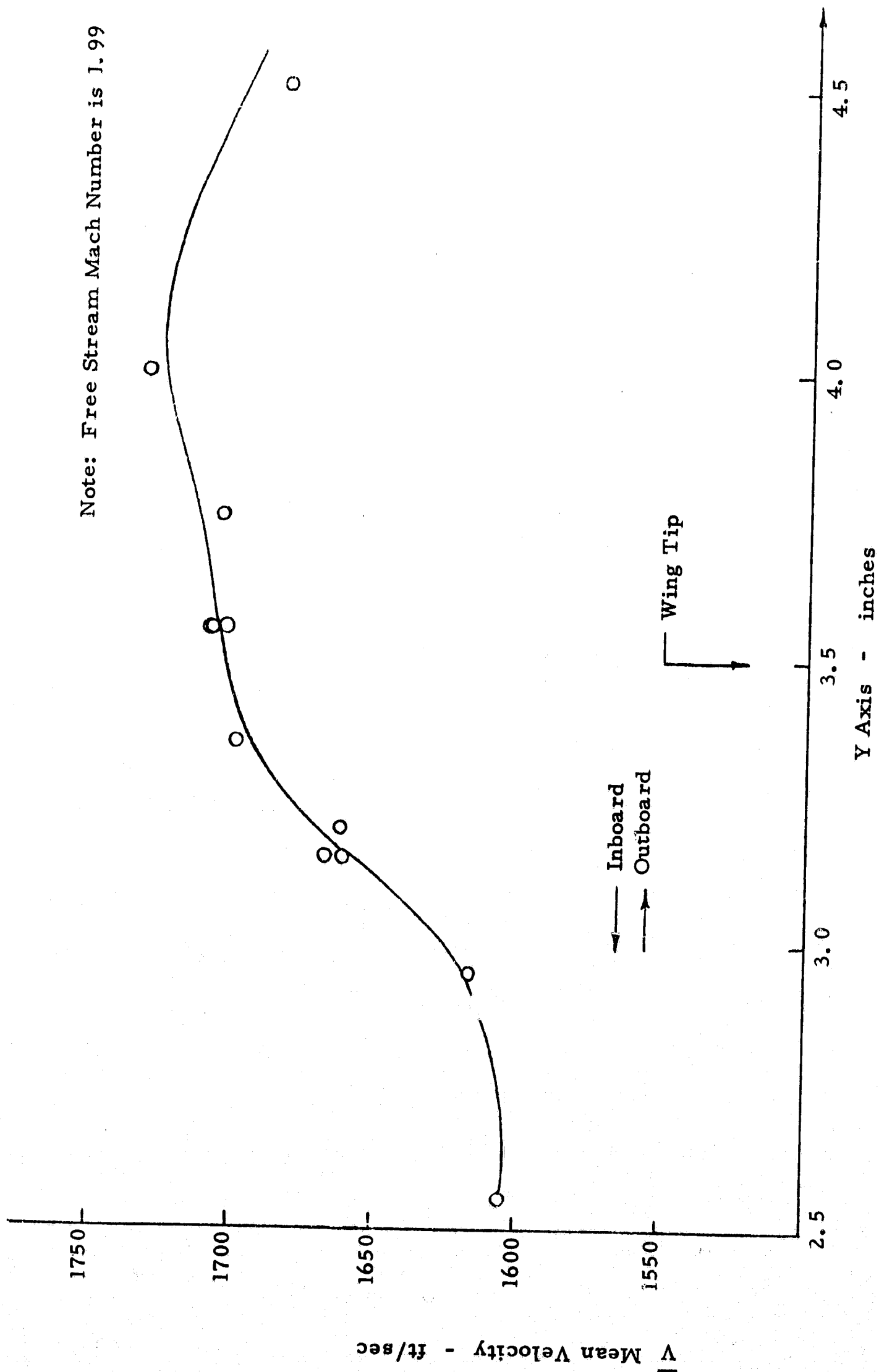
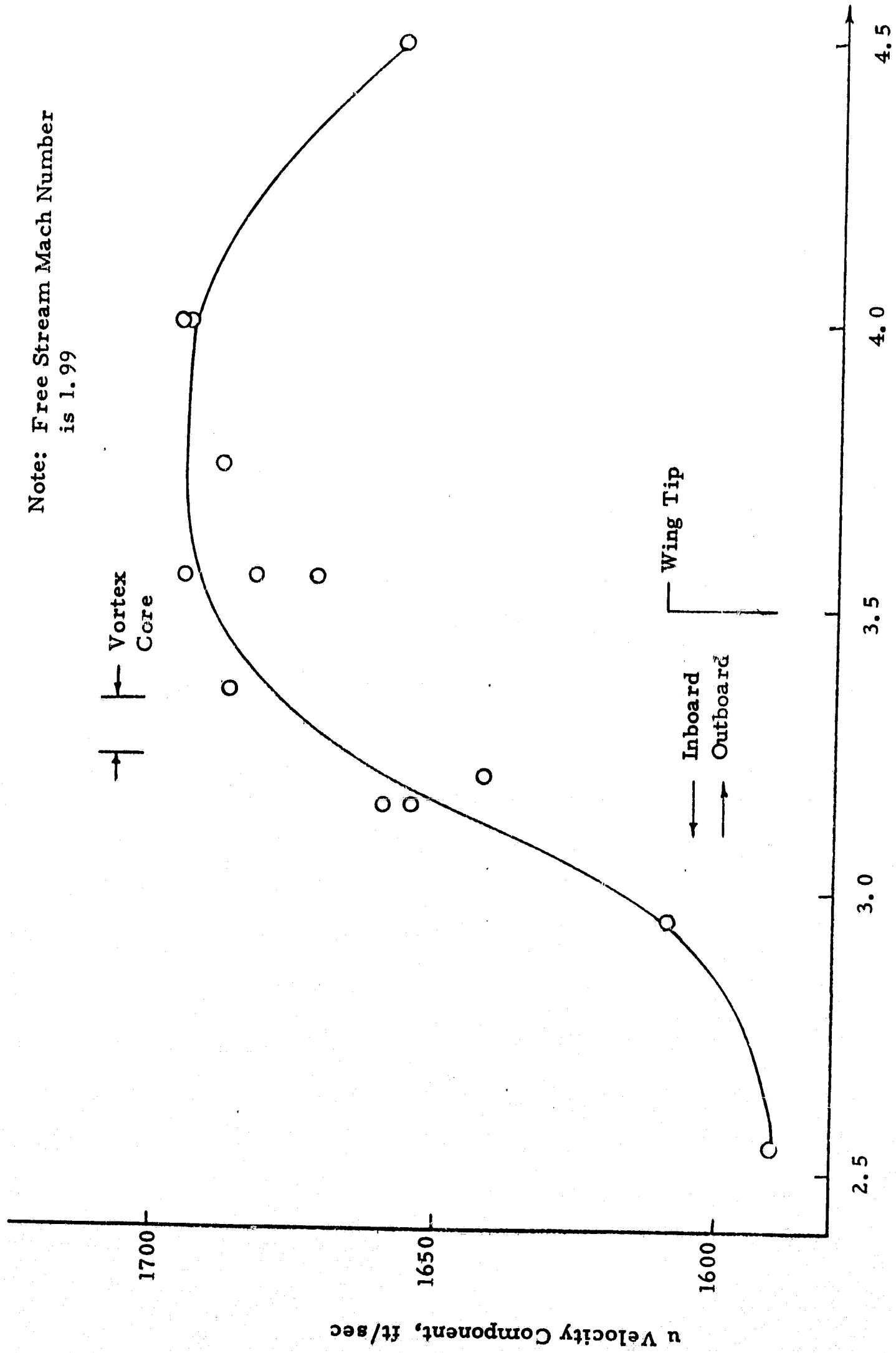


Figure 33. Mean Velocity Profile at $X = 2.50''$, $Z = -0.375''$ in 7-Inch Wind Tunnel with Biconvex Wing at $+6^\circ$ Angle of Attack



Y - Axis - inches

Figure 34. u Velocity Component Profile at $X = 2.5"$, $Z = -0.375"$ in 7-Inch Wind Tunnel with Biconvex Wing at $+6^\circ$ Angle of Attack

Note: Free Stream Mach Number is 1.99

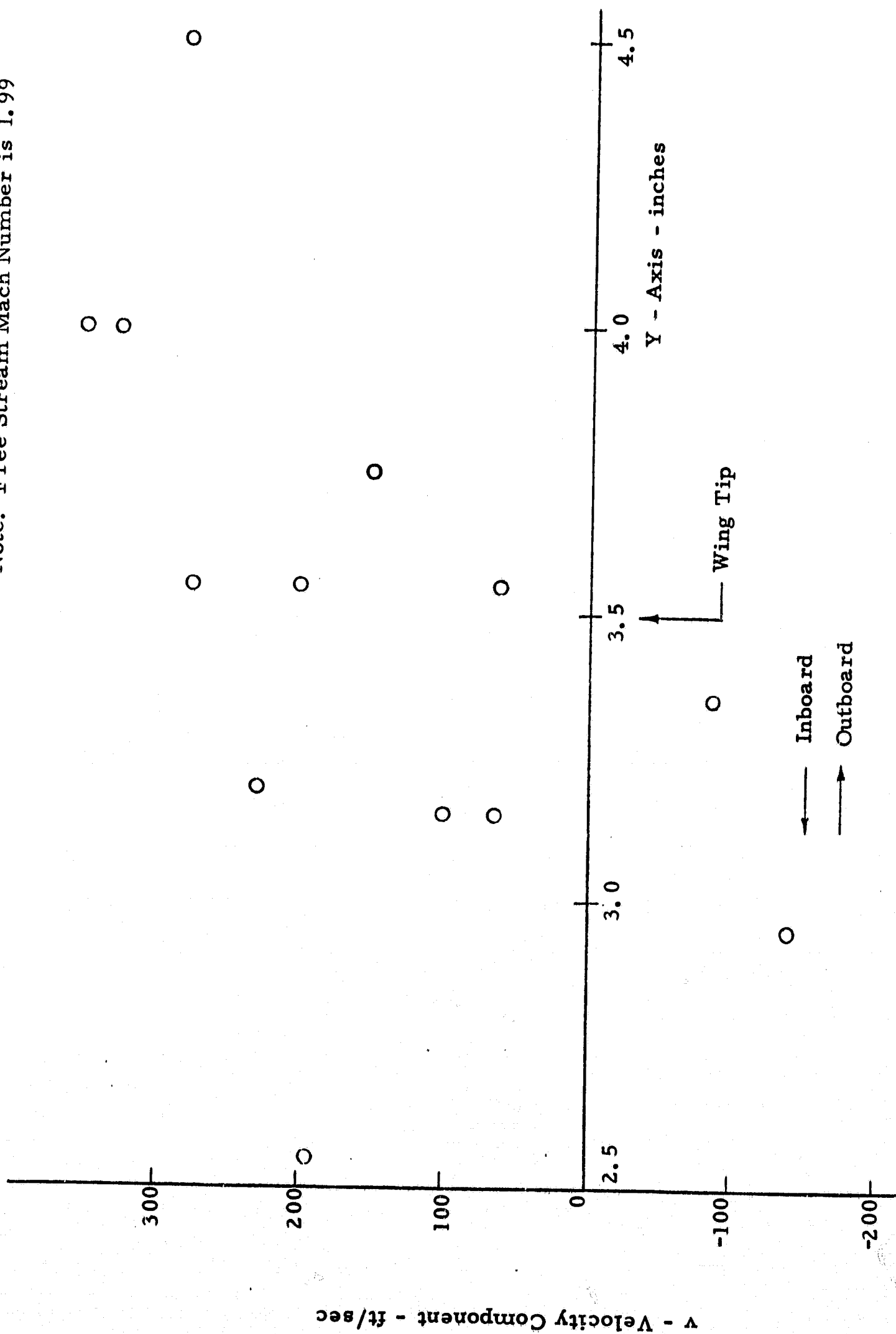


Figure 35. v Velocity Component Profile at $X = 2.50$ ", $Z = -0.375$ " in 7-Inch Wind Tunnel with Biconvex Wing at $+6^\circ$ Angle of Attack

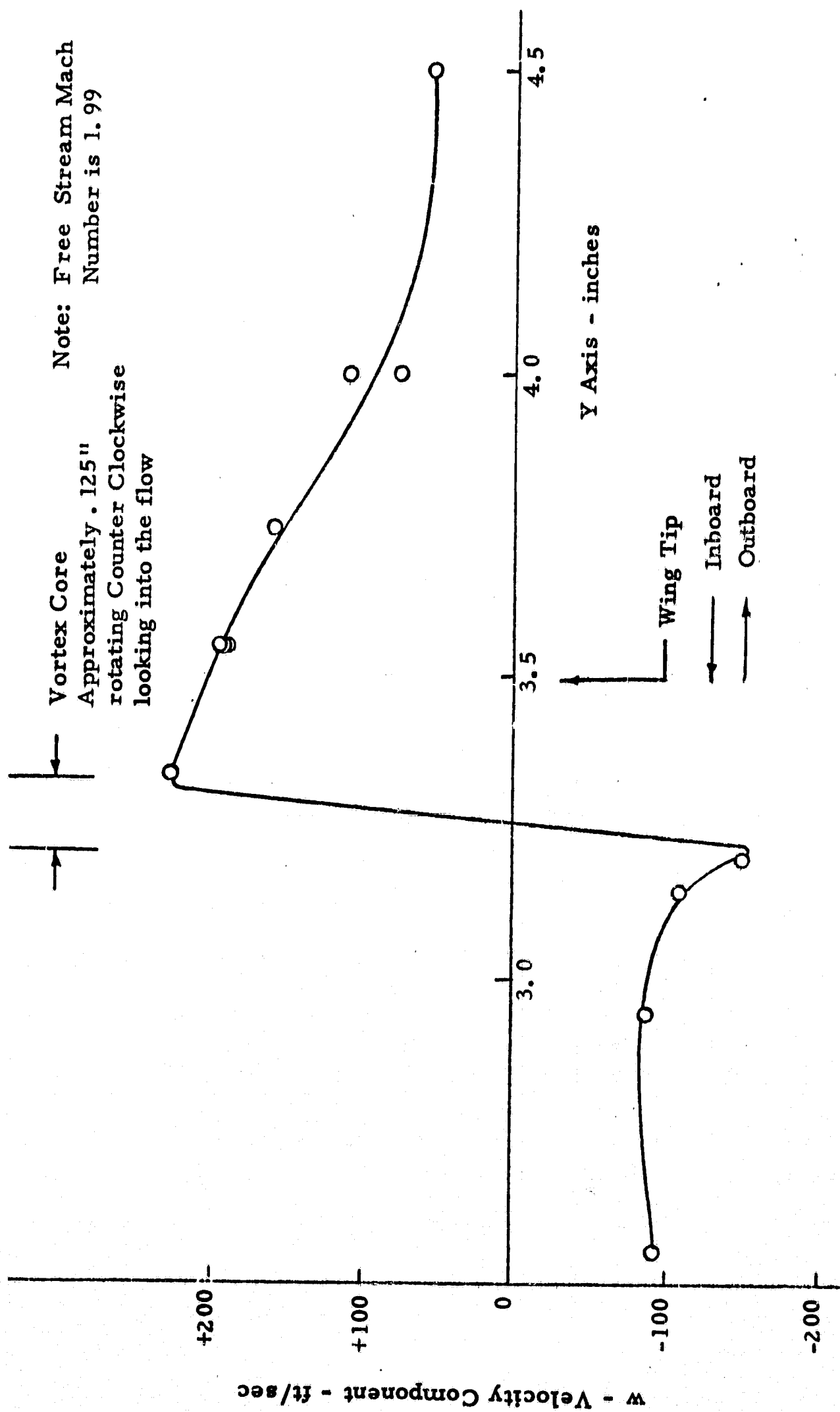


Figure 36. w Velocity Component Profile at $X = 2.50$ ", $Z = -0.375$ " in 7-Inch Wind Tunnel with Biconvex Wing at $+6^\circ$ Angle of Attack

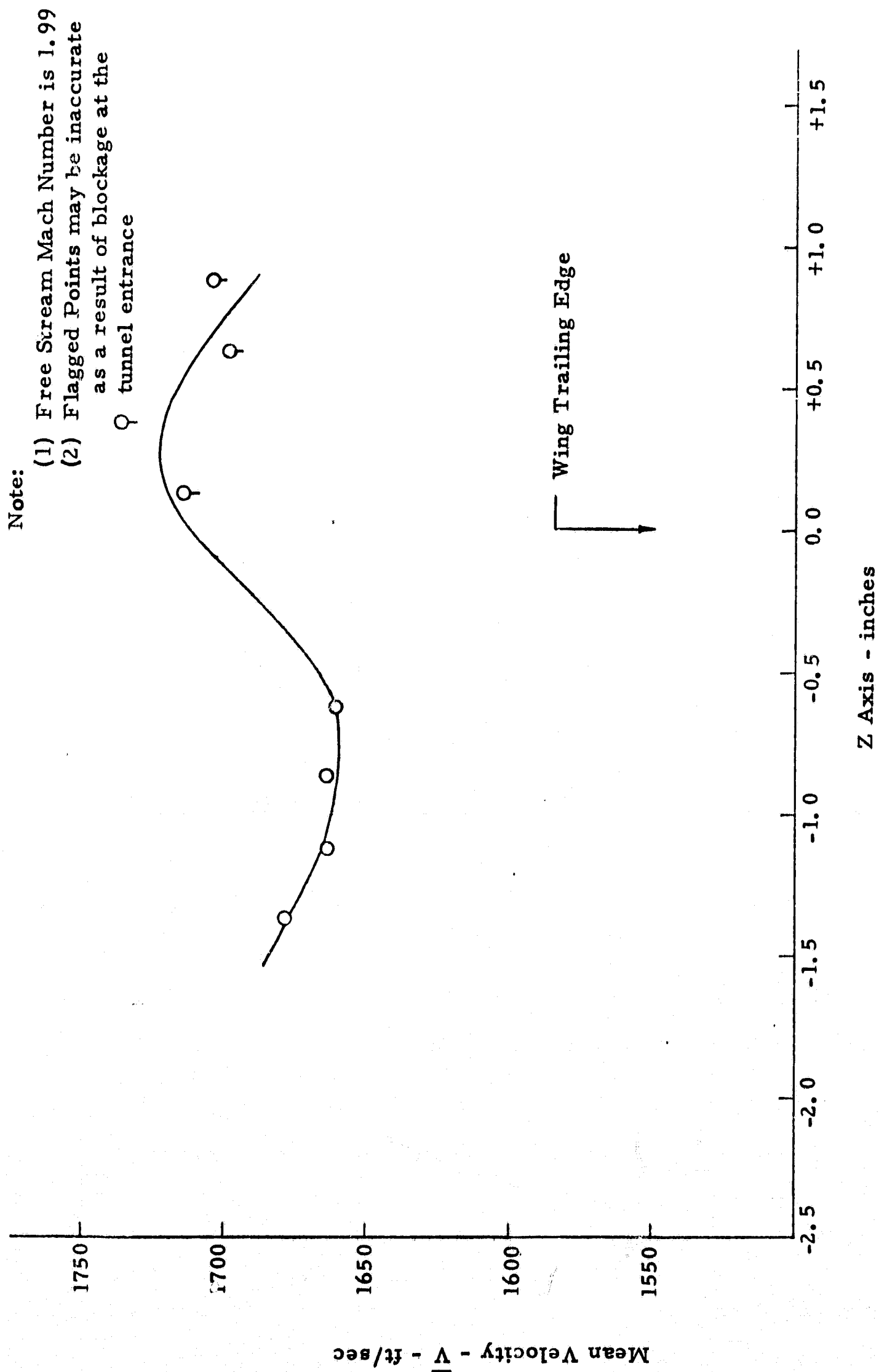


Figure 37. Mean Velocity Profile at $X = 2.50''$, $Y = 3.25''$ in 7-Inch Wind Tunnel with Biconvex Wing at 6° Angle of Attack

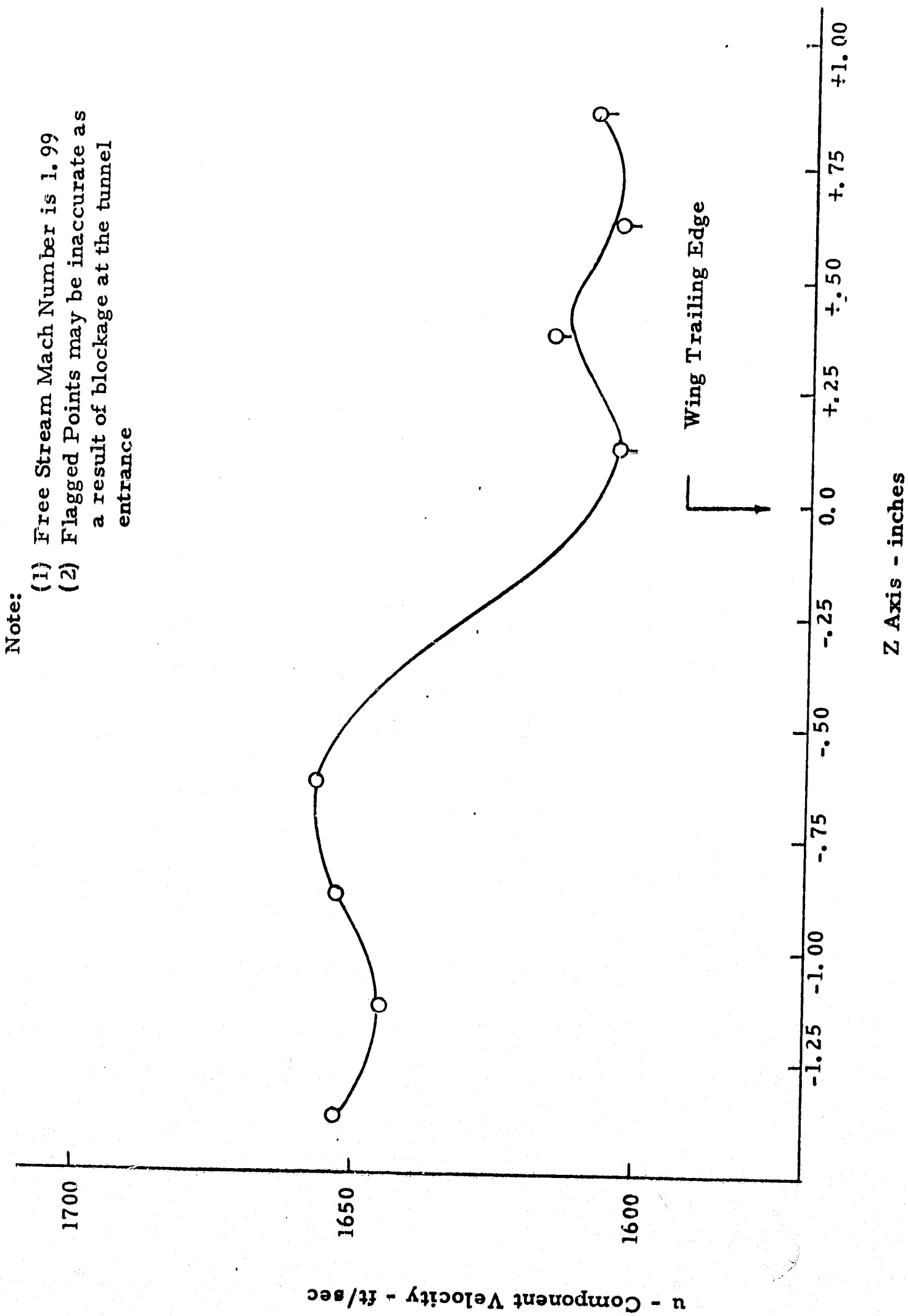


Figure 38. u Velocity Component Profile at $X = 2.50''$, $Y = 3.25''$ in 7-Inch Wind Tunnel with Biconvex Wing at 6° Angle of Attack

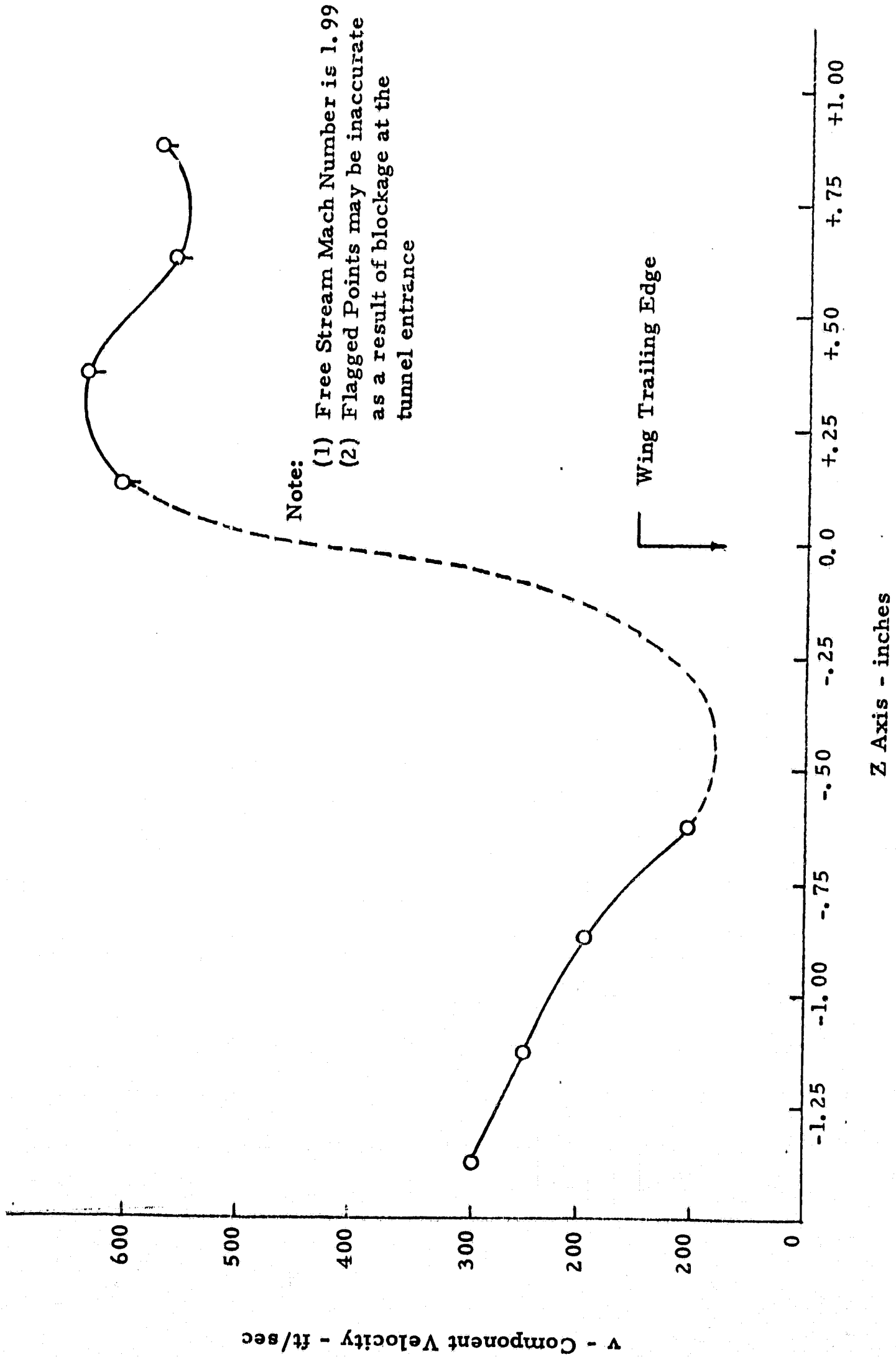


Figure 39. v Velocity Component Profile at $X = 2.50''$, $Y = 3.25''$ in 7-Inch Wind Tunnel with Biconvex Wing at $+6^\circ$ Angle of Attack

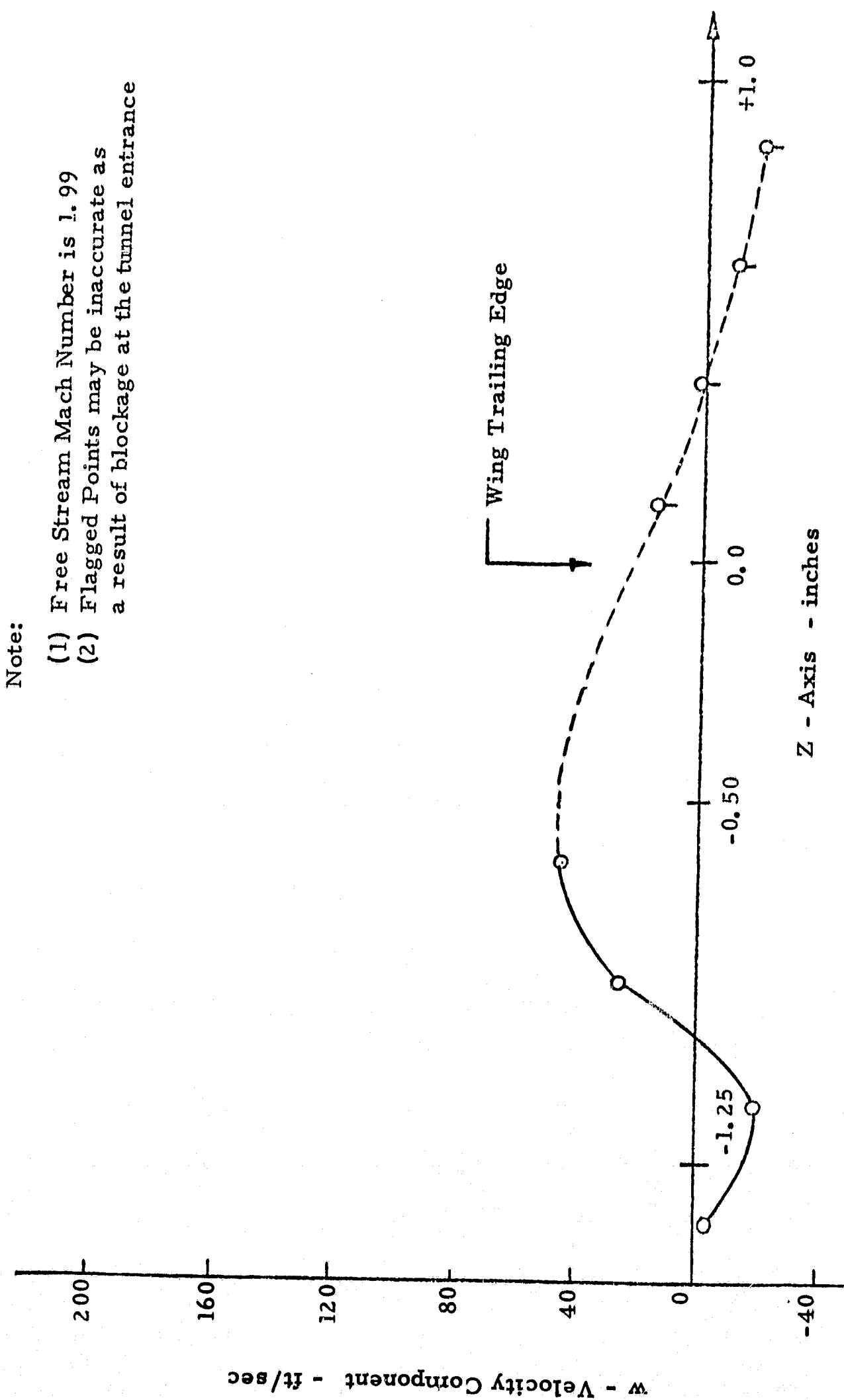


Figure 40. w - Velocity Component Profile at $X = 2.50''$, $Y = 3.25''$ in 7-Inch Wind Tunnel with Biconvex Wing at $+6^\circ$ Angle of Attack