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I am submitting herewith a thesis written by James E. Winchester entitled "Investigation of the Feasibility of Utilizing a Laser Velocimetry System for Air-Jet Flow Analysis in the University of Tennessee Space Institute's Aero-Acoustics Laboratory." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.

James R. Maus

James Maus, Major Professor

We have read this thesis
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Eugene C. Hudson

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L. Evans Roth

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INVESTIGATION OF THE FEASIBILITY OF UTILIZING A LASER VELOCIMETRY SYSTEM FOR AIR-JET FLOW ANALYSIS IN THE UNIVERSITY OF TENNESSEE SPACE INSTITUTE'S AERO-ACOUSTICS LABORATORY

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

James E. Winchester

June 1981

3051864

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Mr. D.B. Brayton and Mr. F.L. Crosswy for their interest and very fine technical advice. He also wishes to thank Mr. Jim Goodman who assisted in the fabrication of hardware and operated the flow facility during the experiments.

ABSTRACT

The purpose of this investigation was to experimentally determine the feasibility of employing a laser velocimetry system for air-jet flow analysis in the University of Tennessee Space Institute's Aero-Acoustics Laboratory. First to be resolved was whether a usable laser velocimetry system could be configured from locally available hardware. Next to be determined was the suitability of the laboratory air supply for laser velocimetry utilization. Specifically, does the air supply inherently contain a sufficient concentration of suitable optical scattering centers with good flow following aerodynamic characteristics? Finally, if a laser velocimetry system could be configured and the laboratory air supply proved suitable for its employment, would a laser velocimetry system actually enhance the laboratory's air-jet flow analysis capability enough to indicate that a more sophisticated system should be procured?

A laser velocimetry system was developed and used for air-jet flow analysis. The lab air supply proved to be suitable and the laser velocimetry system did enhance the air flow analysis capability of the lab.

Data were taken to determine the data acquisition time rate versus laser power at a given flow condition. Data were also taken at several air-jet velocities to determine the flow following characteristics of the optical scattering centers. In addition, data were taken to profile the velocity across a slot nozzle.

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SYMBOLS

A_1 Amplitude of signal component due to source one.

A_2 Amplitude of signal component due to source two.

a $1/e^2$ radius of laser beam at incidence on converging lens.

a_o $1/e^2$ radius of laser beam in the focal or transition region after passage through the converging lens.

b $1/e^2$ depth dimension of the probe volume.

D Separation distance between the parallel laser beams at incidence on the converging lens.

d Fringe separation distance in the probe volume.

e Natural log base (2.7182818).

$\hat{e}_i$ Unit vector in the direction of incidence.

$\hat{e}_n$ Unit vector in a direction normal to the probe volume fringe planes.

$\hat{e}_s$ Unit vector in the direction of scatter.

F Focal length of a lens.

f_d Doppler shift frequency.

f_o Frequency of the incident laser light.

f_s Frequency of the scattered laser light after being Doppler shifted.

h $1/e^2$ height dimension of the probe volume.

θ Angle of intersection of laser beams.

I General optical signal intensity.

I_o Optical intensity at the laser beam center or axis.

I_s Optical intensity of scattered signal.

λ Wavelength of light in a given medium.

λ_o Wavelength of light in free space.

ℓ $1/e^2$ length dimension of the probe volume.

M Total number of individual measurements.

η Index of refraction of a given medium.

r Radial distance.

TI Turbulence intensity of a flow field.

τ Time period of one cycle of a periodic signal.

$\overline{V}$ Instanteous velocity.

$\overline{Vm}$ Mean velocity.

CHAPTER I

INTRODUCTION

In many applications fluid flow analysis utilizing a mechanical probe is either physically impractical or undesirable because the probe would perturb the flow. Also in hot or corrosive fluids and in very high velocity flows mechanical probes might lack survivability. Laser velocimetry offers an alternative approach in that no material sensor need be placed in the flow field to detect the characteristics of the flow. Instead the area of interest is illuminated by laser light. The only perturbation to the flow is due to photon interaction with elements of the flow. This interaction is essentially non-perturbing when compared to the interaction due to a material probe.

The utilization of a laser velocimetry system for flow analysis is contingent upon detecting laser light which has been scattered by elements of the flow. The scattered laser light carries intelligence about the scattering medium in the form of frequency and amplitude modulation. The frequency modulation or Doppler frequency shift is directly proportional to the velocity of the scattering medium relative to the observer or detector. The Doppler frequency shift of the scattered laser light may be expressed as:

$$f_d = f_s - f_o = \frac{n\,\bar{V}}{\lambda_o} \cdot (\hat{e}_s - \hat{e}_i) \qquad (1)$$

Note a directional dependence of the Doppler frequency shift on the direction of scatter in addition to the direction of incidence.

Equation (1) assumes a single illuminating source or laser beam.

Consider the case of two similar sources illuminating a scattering medium from different directions. A detector will now respond to two different, yet simultaneously scattered fields. The Doppler shift frequency of source one may be expressed as:

$$f_{d1} = f_{s1} - f_o = \frac{n\bar{V}}{\lambda_o} \cdot (\hat{e}_s - \hat{e}_{i1}) \tag{2}$$

The Doppler shift frequency of source two may be expressed as:

$$f_{d2} = f_{s2} - f_o = \frac{n\bar{V}}{\lambda_o} \cdot (\hat{e}_s - \hat{e}_{i2}) \tag{3}$$

The scattered light at the detector is the combination of the two scattered fields. The intensity of the light at the detector due to the combination of the two scattered fields may be expressed as:

$$I_s = A_1^2 + A_2^2 + 2A_1A_2\cos\left(2\pi\left[f_{s1} - f_{s2}\right]t\right) \tag{4}$$

The two scattered fields are heterodyned at the detector to produce a field which is amplitude modulated at a frequency equal to the frequency difference of the scattered fields.

From equations (2) and (3) the scattered field frequencies are:

$$f_{s1} = f_o + f_{d1} \tag{5}$$

$$f_{s2} = f_o + f_{d2} \tag{6}$$

and the frequency difference is thus:

$$f_{s1} - f_{s2} = (f_o + f_{d1}) - (f_o + f_{d2}) = f_{d1} - f_{d2} \tag{7}$$

As can be seen this frequency difference is the difference in the Doppler frequency shifts. This can be expressed as:

$$f_{d1} - f_{d2} = \frac{n\bar{V}}{\lambda_o} \cdot (\hat{e}_{i1} - \hat{e}_{i2}) = \frac{n\bar{V} \cdot \hat{e}_n}{\lambda_o} (2\sin\theta/2) \tag{8}$$

A laser velocimetry system which is based on this relationship is referred to as either a dual scatter or differential Doppler system. Note from equation (8) that the differential Doppler frequency is independent of the direction of scatter. This being the case a very large collecting aperture can be utilized to detect the scattered light. This is a very practical advantage over single scatter systems since the large collection aperture enhances system sensitivity.

Since only a low power ($\sim$ 5mW) Helium-Neon laser was available for this work, a differential Doppler laser velocimetry configuration was chosen. The need to configure the laser velocimetry system for high sensitivity was compounded by the fact that photomultiplier tubes have a relatively low spectral response at the 6328 Angstrom wavelength of Helium-Neon laser.

A practical differential Doppler system utilizes two illuminating sources which are monochromatic, plane-polarized, TEMoo laser beams. Typically the two beams are the results of a single laser beam which has been optically split. The two beams are converged to an intersection area called the probe volume. The probe volume is the area in which the criteria for differential Doppler scattering is met. A small particle passing through the probe volume is illuminated by the two sources and thus scatters from both simultaneously. A lens is utilized to converge the two laser beams. If the beams are parallel before incidence on the lens they will be brought to focus at the point of intersection. The probe volume can thus be a small volume of space and velocity measurements made with such a differential Doppler velocimetry system are very much localized.

The probe volume may be analyzed from the standpoint of optical interference phenomena. We have restricted the sources illuminating the probe volume space to monochromatic, plane-polarized, TEMoo laser beams. This being the case, there will exist interference fringes in the probe volume space if beam polarization is not exactly orthogonal. If we additionally specify that the intensity of the two beams be equal and that their polarization be in the same direction, we will maximize the interference effects. That is, the highest contrast between bright and dark fringes will be achieved.

Figure 1 illustrates two-dimensionally the formation of interference fringes in the probe volume. In the actual probe volume the fringes will be planes.

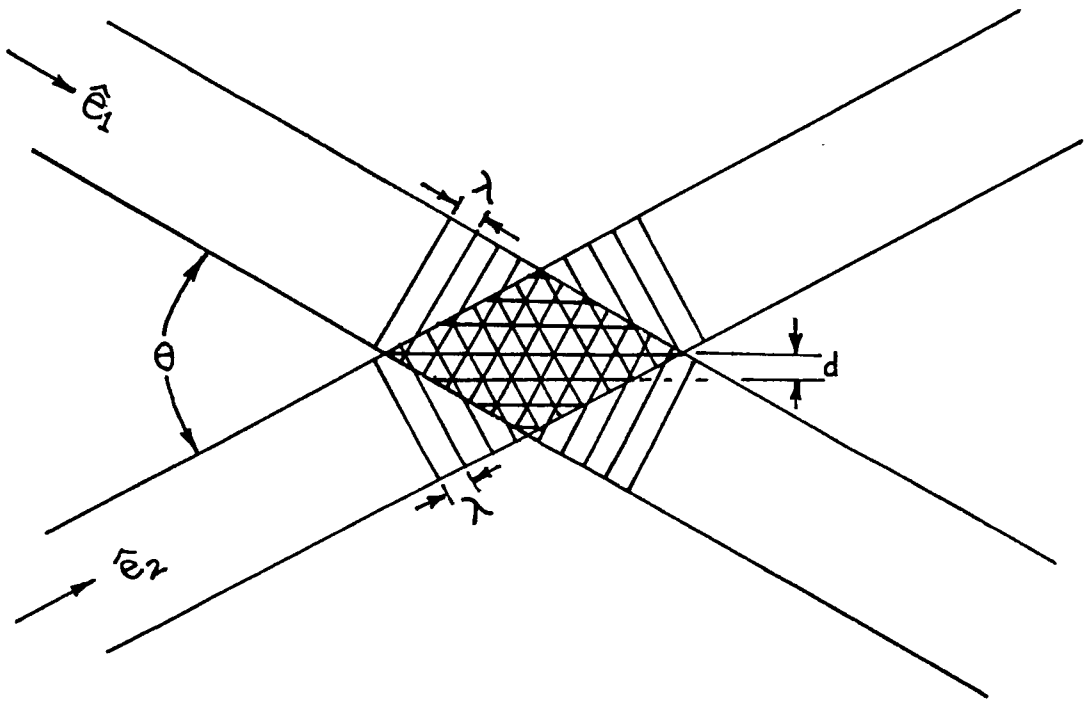


Figure 1. Two-Dimensional Illustration of Intersecting Laser Beams Forming Interference Fringes

The fringe planes are parallel to the bisector of the beam intersection angle and perpendicular to the plane defined by the crossed beams. The distance between two adjacent bright or dark fringes may be expressed as:

$$d = \frac{\lambda}{2\,\mathrm{SIN}(\theta/2)} \tag{9}$$

Knowing the laser wavelength and beam intersection angle one can readily determine the probe volume fringe spacing.

A small particle passing through the probe volume will scatter light which has an intensity variation or envelope with frequency given by:

$$f_D = \frac{\bar{V}\cdot(\hat{e}_1 - \hat{e}_2)}{d} \tag{10}$$

Since $(\hat{e}_1-\hat{e}_2)$ is a vector orthogonal to the planar fringes, (f_D) is seen to be proportional to the component of velocity orthogonal to the fringe planes. The velocity component is expressed as:

$$\bar{V}\cdot\hat{e}_n = f_D \times d = \frac{f_D\,\lambda}{2\,\mathrm{SIN}(\theta/2)} \tag{11}$$

As can be seen, one need only detect and measure the envelope frequency of light scattered from the probe volume to determine a component of velocity of the scatterer. This, of course, assumes that the laser wavelength and angle of intersection are known. This envelope frequency is the same as the differential Doppler frequency.

It is intuitatively obvious at this point that the measured component of velocity could be orthogonal to the probe volume fringe planes from either side and produce the same results. There is thus a directional ambiguity in measurements made with a laser velocimetry system configured as just described. To effectively utilize such a system one must know

the general direction of the flow to be measured.

A method of overcoming this directional ambiguity is to shift the optical frequency of one of the laser beams prior to the probe volume intersection. This causes the interference fringes to move through the probe volume in a direction orthogonal to their plane. The envelope frequency of light scattered from the probe volume will thus be either up-shifted or down-shifted depending on the direction through which the scatterer traverses the probe volume. If this fringe travel velocity is made to be greater than the flow velocity, then the velocimetry system can have a directional sense.

The laser velocimetry system which was configured for air-jet flow analysis did not have directional sense. Its application was thus limited; however, the objectives of the investigation could be met with such a system.

The size and shape of the probe volume as well as the light intensity distribution within it will now be considered. In order to characterize the probe volume one must first characterize the laser beams which produce it. This discussion is limited to the characteristics of laser beams similar to that of the laser which was utilized for this work. Specifically, the laser beams are monochromatic with a circular cross section Gaussian intensity distribution and plane-polarized TEMoo mode. Also the crossing beams shall be of equal intensity and polarized in the same direction.

Gaussian intensity distribution is maximum at the center of the beam with an exponential decrease with radial distance from the center or axis of the beam. Equation (12) defines the intensity across a Gaussian beam.

$$I = I_o \, e^{(-2r^2/a^2)} \qquad (12)$$

Figure 2 is a plot of a Gaussian distribution.

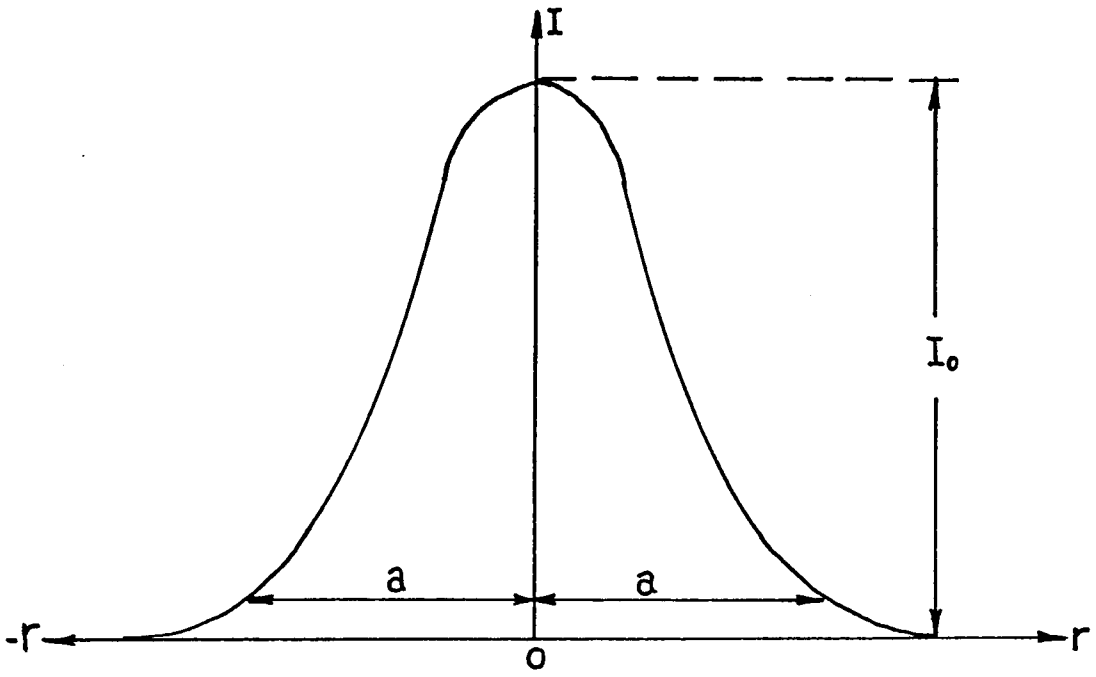


Figure 2. Plot of Typical Gaussian Distribution

The distance a is defined as the radial distance from the beam axis to the location where beam intensity has decreased to $1/e^2$ times the intensity at the axis.

The laser beams which form the probe volume are made to intersect by a converging lens. The laser beam wave fronts are planar upon incidence with the converging lens. The lens transforms the planar wave fronts to converging spherical wave fronts. The converging spherical wave fronts do not converge to an infinitely small point, but pass through a transition region where they are again planar wave fronts. Upon leaving the transition region the wave fronts become diverging spherical waves. Figure 3 below illustrates this phenomena.

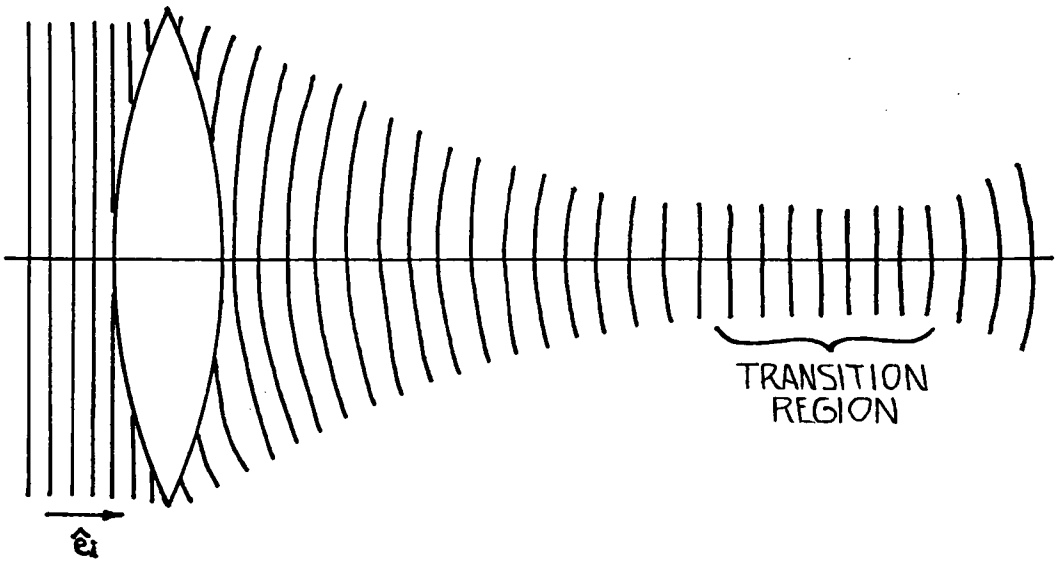


Figure 3. Illustration of Wave Fronts After Passage Through Converging Lens

When two parallel beams are made to intersect by a conversing lens the intersection will occur in the transition region of both beams. The wave fronts in the intersection region which form the probe volume will thus be planar. Figure 4, which follows, illustrates the intersection of two beams due to passage through a converging lens.

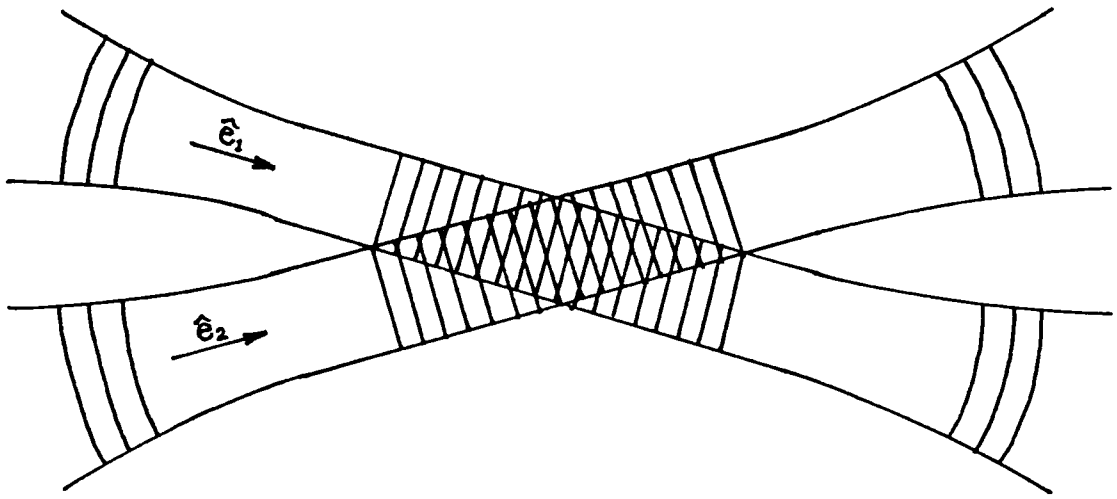


Figure 4. Illustration of Wave Fronts of Two Parallel Laser Beams After Passing Through a a Converging Lens

The diameters of the beams in the intersection area must be known to define the probe volume dimensions. If the $1/e^2$ diameters of the beams at incidence to the converging lens are 2a, then the $1/e^2$ diameters in the probe volume are given by equation (13):

$$2a_o = 4\lambda F / \pi 2a = 2\lambda F / \pi a \qquad (13)$$

F is the focal length of the converging lens.

The intensity distribution in the transition region is Gaussian so the probe volume also has a Gaussian intensity distribution. Figure 5 illustrates the $1/e^2$ intensity contour of the probe volume.

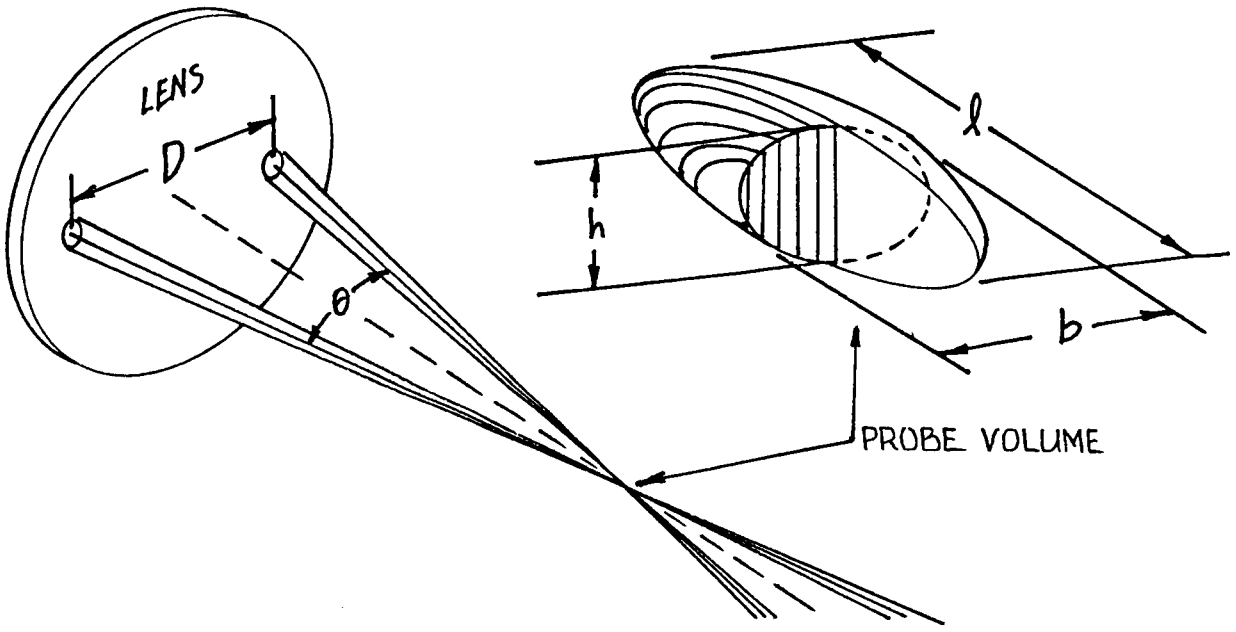


Figure 5. $1/e^2$ Intensity Contour of a Probe Volume

Note that the probe volume is an ellipsoid whose dimensions depend on the $1/e^2$ beam diameter and the angle of beam intersection. Equations (14), (15), and (16) define the height, length, and depth of the probe volume.

$$h = 2a_o = 2F\lambda/\pi a \tag{14}$$

$$\ell = 2a_o/\mathrm{SIN}(\theta/2) = 2F\lambda/\pi a\,\mathrm{SIN}(\theta/2) \tag{15}$$

$$b = 2a_o/\mathrm{COS}(\theta/2) = 2F\lambda/\pi a\,\mathrm{COS}(\theta/2) \tag{16}$$

Knowing the fringe spacing, d, from equation (9) and the probe volume depth, b, from equation (16), one can determine the number of fringes, N, in the probe volume by equation (17).

$$N = b/d = (4F/\pi a)\mathrm{TAN}(\theta/2) \tag{17}$$

From Figure 5 equation (18) follows.

$$\mathrm{TAN}(\theta/2) = D/2F \tag{18}$$

Equation (17) thus reduces to.

$$N = 2D/\pi a \tag{19}$$

The number of fringes in the $1/e^2$ intensity probe volume is dependent on the ratio of the parallel beam separation to the $1/e^2$ intensity radius of the beams at incidence to the converging lens.

The probe volume has now been characterized and can be analyzed from known or measurable parameters associated with the laser beams and the lens which converges them to intersection.

As previously stated, the key to the utilization of a laser velocimetry system is the detection of laser light which has been scattered by

elements of the flow. Every medium through which light propagates except an absolute vacuum must scatter some portion of the light. Even rarified gases and air scatter light because there are short range variations in the local index of refraction, i.e., molecules interspersed with vacuum. Scattering by small gas molecules is, however, extremely slight and detection of this scattered light is impractical for laser velocimetry at this time. To measure air velocity with a laser velocimetry system, requires that impurities be entrained in the air flow which will scatter detectable levels of the probe volume laser light. The impurities may be inherently present in the air or added by seeding the air supply. These impurities are usually called scatter centers or simply scatterers.

If a scatterer is to be suitable for laser velocimetry utilization, it must have good flow following characteristics. From this standpoint small size and low density are favorable scatterer properties. A suitable scatterer must also scatter enough light to be detected during its transit of the probe volume. From this standpoint a high index of refraction, which is proportional to density, and a large size are figures of merit. Ideal scatterers are those which follow the flow in question and also scatter enough light for proper detection.

The upper limit on scatterer size is determined by the probe volume fringe spacing. Scatterers which have dimensions less than the fringe spacing generally produce signals with the highest peak to peak level. This is because they may pass through regions of the probe volume completely out of any bright fringe. Scatterers whose dimensions are greater than the fringe spacing are always partially illuminated in the probe volume. Figure 6 illustrates the intensity variation of light scattered from a probe volume by a scatterer whose dimensions are less than the

probe volume fringe spacing. Figure 7 illustrates intensity variations due to scattering by a scatterer whose dimensions are greater than the probe volume fringe spacing.

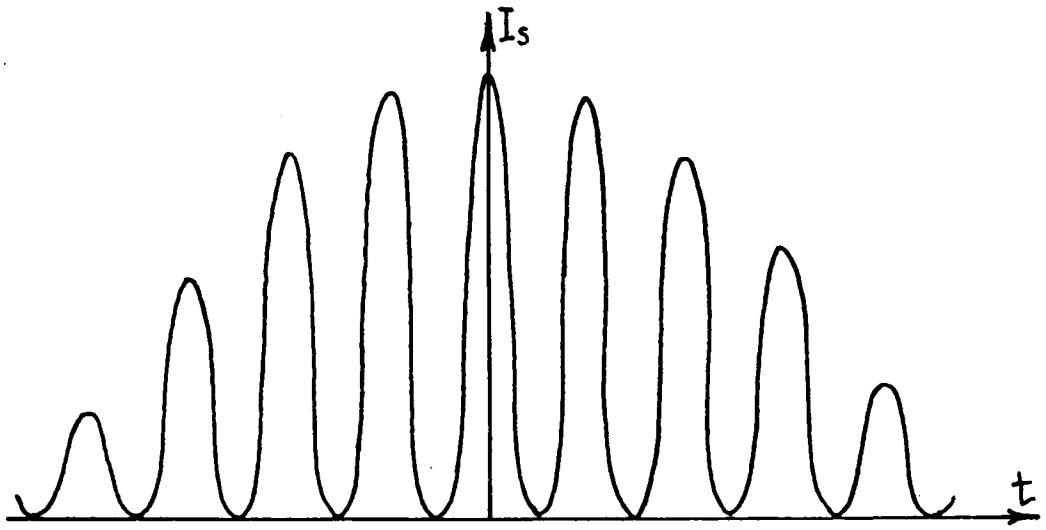


Figure 6. Intensity Distribution of Signal Generated by a Scatter Center with Dimensions Less Than the Probe Volume Fringe Spacing

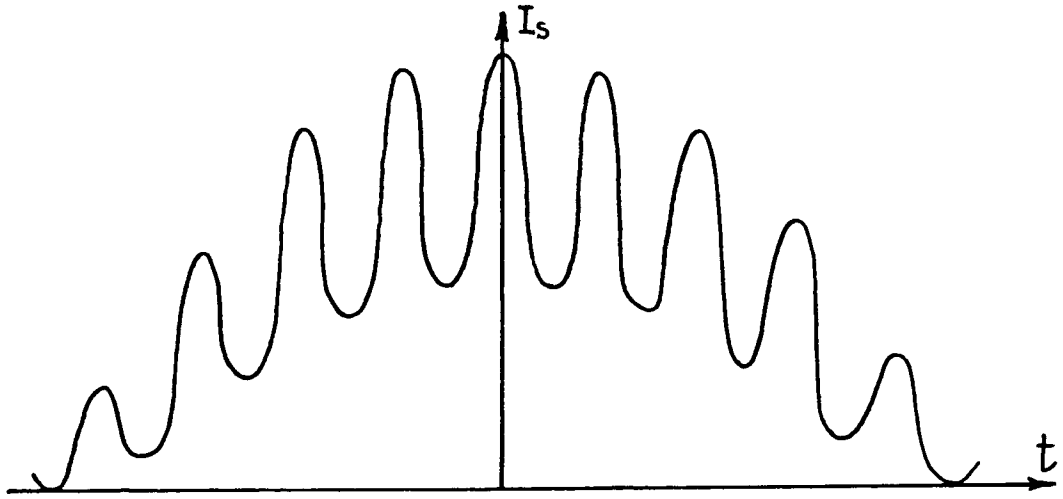


Figure 7. Intensity Distribution of Signal Generated by a Scatter Center With Dimensions Greater Than the Probe Volume Fringe Spacing

Note from Figure 7 that the intensity of light scattered by a scatterer with dimensions greater than the fringe spacing does not decrease to zero during its passage through the probe volume, but has a pedestal or lower level envelope. In general the height of the pedestal increases as the size of the scatterer increases. Although this is undesirable for laser velocimetry work, particle sizing techniques have been developed based on this fact. For laser velocimetry applications the higher peak to peak signals are more desirable because they are due to smaller scatterers which are more apt to be good flow followers and the signals are more readily analyzed electronically for velocity determination.

The intensity of laser light scattered by a scatterer traversing the probe volume varies with direction. For typical scatterers suitable for laser velocimetry applications the intensity of scattered light is greatest in the direction of incidence. This being the case, highest system sensitivity is achieved by locating the receive optics forward of the probe volume. Since the scattered light is due to two sources with different directions of incidence, the ideal receive direction is along the bisector of the angle formed by the two beams. In this case maximum equal intensities of scattered light from each source may be collected. Figure 8 illustrates the typical directionality of light scattered from the probe volume by suitable scatterers.

The function of the receive optics is to collect laser light scattered from the probe volume by elements of the flow and to direct this scattered light to the photocathode of a photomultiplier tube. Light scattered from the probe volume radiates outwardly in approximate spherical wave fronts. Access to the photomultiplier tube's photocathode is through an opening which should be as small as possible to prevent

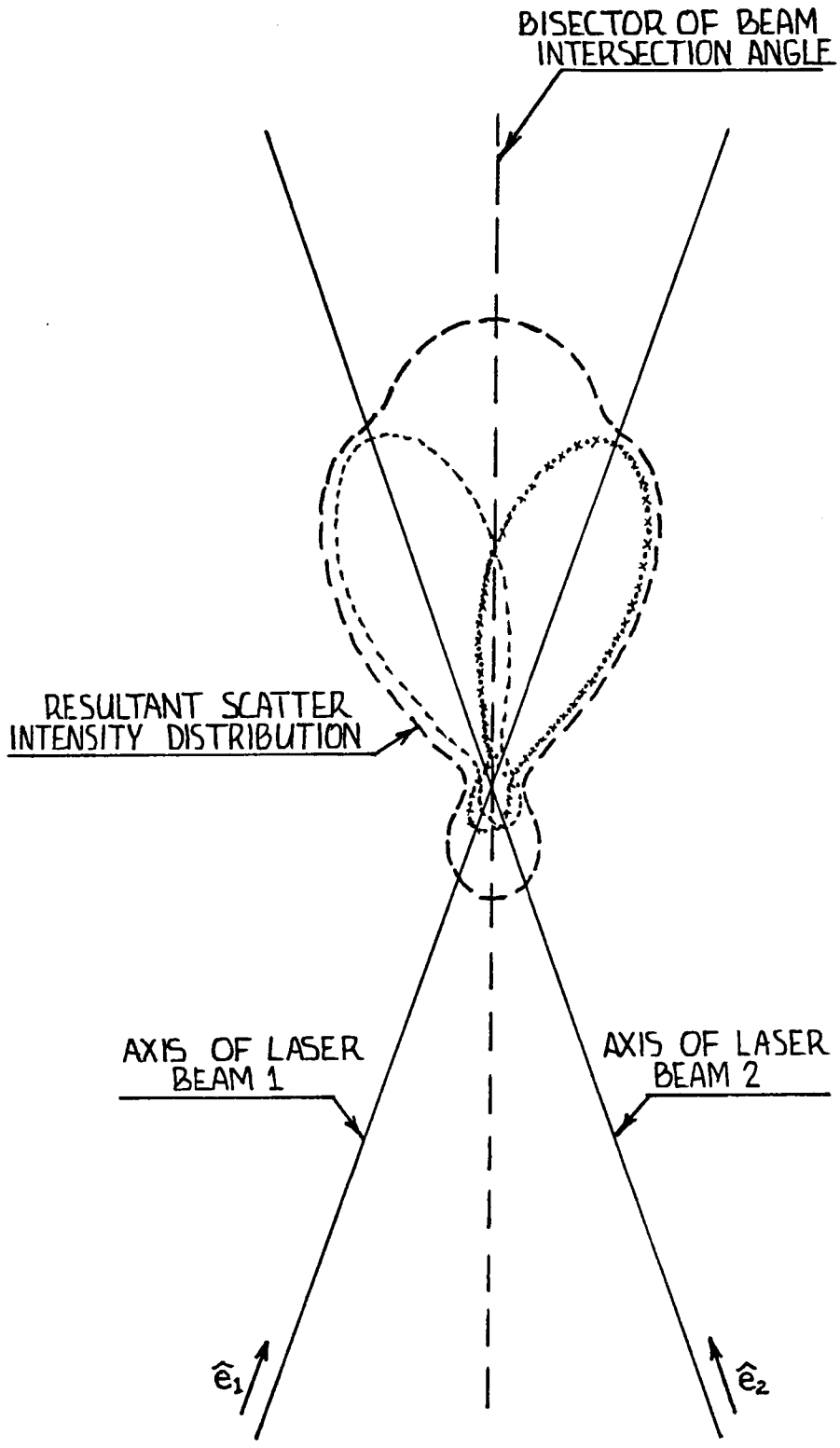


Figure 8. Typical Directional Distribution of Light Scattered from the Probe Volume by a Scatter Center

interference from extraneous light sources. With these factors in mind, the receive optics must collect the diverging scattered light and converge it to a point for entry into the photomultiplier tube. Figure 9 shows a typical receive optics configuration.

The optics system depicted in Figure 9 projects the image of the probe volume at the pin-hole aperture in front of the photomultiplier tube. If all the light scattered from the probe volume and collected by the receive optics is to enter the photomultiplier tube the pin-hole aperture must be at least as large in diameter as the probe volume depth, b. If the pin-hole aperture is smaller than b the effective size of the probe volume is reduced to the smaller pin-hole size. This effect may be utilized to enhance the localization of a laser velocimetry measurement.

The photomultiplier tube converts the intensity of incidence light to an electrical current. Since the intensity of light scattered from the probe volume is modulated by the scatterer's traversing of bright and dark fringes the electrical current in the photomultiplier tube must vary accordingly. The photomultiplier tube thus acts as a demodulator and converter, producing an electrical signal proportional to the intensity variation of light incident upon its photocathode. The frequency of the electrical signal must be measured to determine the velocity of the scatterer.

For air flow analysis, signals are generated when entrained scatterers randomly traverse the probe volume. The signals generated are referred to as Doppler bursts. Doppler bursts are typically of very short durations compared to the time interval between their occurrence. Various methods exist for determining the frequency of a detected Doppler

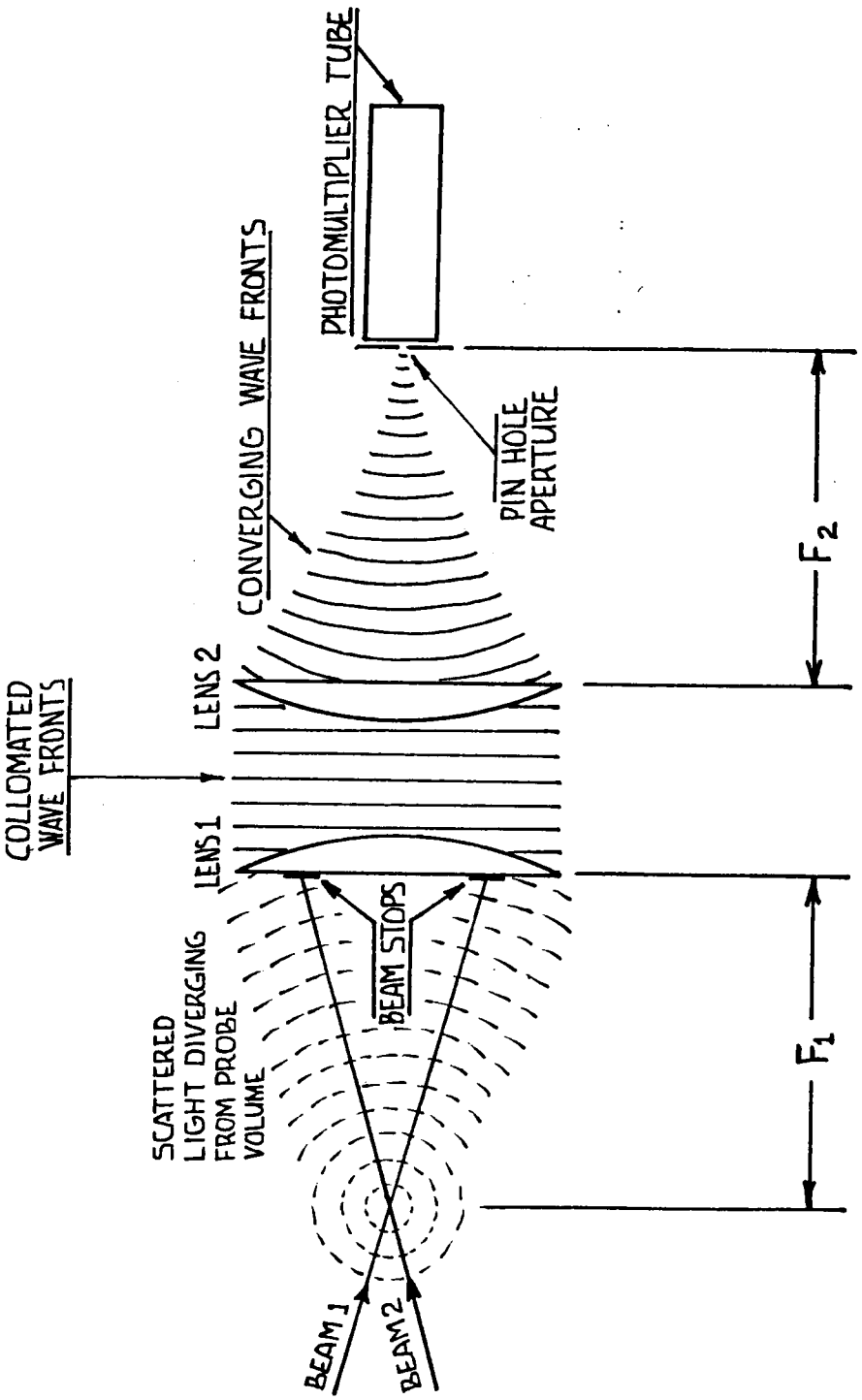


Figure 9. Illustration of Receive Optics Configuration

burst signal. The simplest and least accurate method is to "capture" a Doppler burst on a storage oscilloscope display and measure the distance between peaks. The Doppler burst signal period, τ, is equal to the product of the measured distance and the oscilloscope sweep rate given in seconds per unit of distance. The velocity of the scatterer may then be determined from equation (11).

Special electronic frequency counters have been developed for Doppler burst signal analysis. These counters very rapidly determine signal period from only a few cycles of signal, output this data to a recording device, then reset and wait for the next Doppler burst. The recording device may be a printer or a paper tape punch or a magnetic storage device associated with a computer system.

Each Doppler burst is a discrete and singular response from the flow field. The velocity represented by the frequency of each Doppler burst may be considered to be instantaneous when the Doppler burst duration is much less than the period of the flow turbulence frequency. In this case, a collection of many individual velocity measurements may be statistically analyzed to determine a mean velocity and a turbulence intensity. Equations (20) and (21) which follow may be used to calculate the mean velocity, Vm, and turbulence intensity, TI, respectively.

$$\overline{V}_m = \left(\sum_{i=1}^{m} V_i / M \right) \tag{20}$$

$$TI = \left[\sum_{i=1}^{m} (V_i - V_m)^2 / (m-1) \right]^{1/2} \tag{21}$$

The number of measurements, m, is very important since the accuracy of the calculated mean velocity and turbulence intensity is proportional to the number of singular measurements used in their calculation.

In summary, the fundamentals necessary for understanding the operation of a differential Doppler laser velocimetry system have been presented. The discussion was limited to single velocity component systems with no sense of direction. It should be pointed out that this is the simplest form of differential Doppler velocimetry system and that two and even three velocity component systems with directional sense have been developed and are in use today. The discussion was also limited to air flow velocity measurements where signals occur randomly due to the passage of small particles through the probe volume. Measurements are made at times in fluids and gases such as smoke where a continuous signal is generated. A continuous signal may be analyzed in the frequency domain by Fast Fourier Transform or other real-time spectrum analyzers. It should also be pointed out that flow analysis measurements made by laser velocimetry systems are direct measurements and not the measurement of effects as is the case with thermal or pressure sensors. In the case of the differential Doppler laser velocimeter the probe volume fringes act as markers with a known separation distance. Velocity determination is the simple matter of timing scatterer passage from fringe to fringe.

CHAPTER II

CONFIGURATION OF THE DIFFERENTIAL DOPPLER LASER VELOCIMETRY SYSTEM UTILIZED FOR THIS INVESTIGATION

The first requirement of this investigation was to fabricate a laser velocimetry system that could be used for air flow analysis. Only the final system will be described here. Figure 10 below shows this system in place adjacent to the stilling chamber and air-jet nozzle with which it was used. Figure 11 shows the optical portion of the system from a position downstream looking back into the air-jet nozzle. Figure 12 schematically illustrates the system.

The Spectra-Physics Model 123 Helium-Neon laser used as the laser velocimetry system source operated in the TEMoo mode with characteristic wavelength of 6328 Angstroms. The optical power of this laser was determined to be 5.6 mW. The laser beam was of circular cross section with a $1/e^2$ intensity diameter of 0.9 mm.

The component following the laser was a parallel plate beam splitter which produced two parallel equal intensity beams from a single beam input. Figure 13 illustrates the shape and action of the beam splitter. The beam polarization was orthogonal to the plane of the surface shown in Figure 13. The separation distance between the centers of the two parallel beams was approximately 5/8 inch.

The optical component following the beam splitter was the converging lens. The converging lens was a plano-convex lens with a focal length of 192 mm. The lens was orientated so that the parallel beams were incident on the convex side as shown in Figure 14.

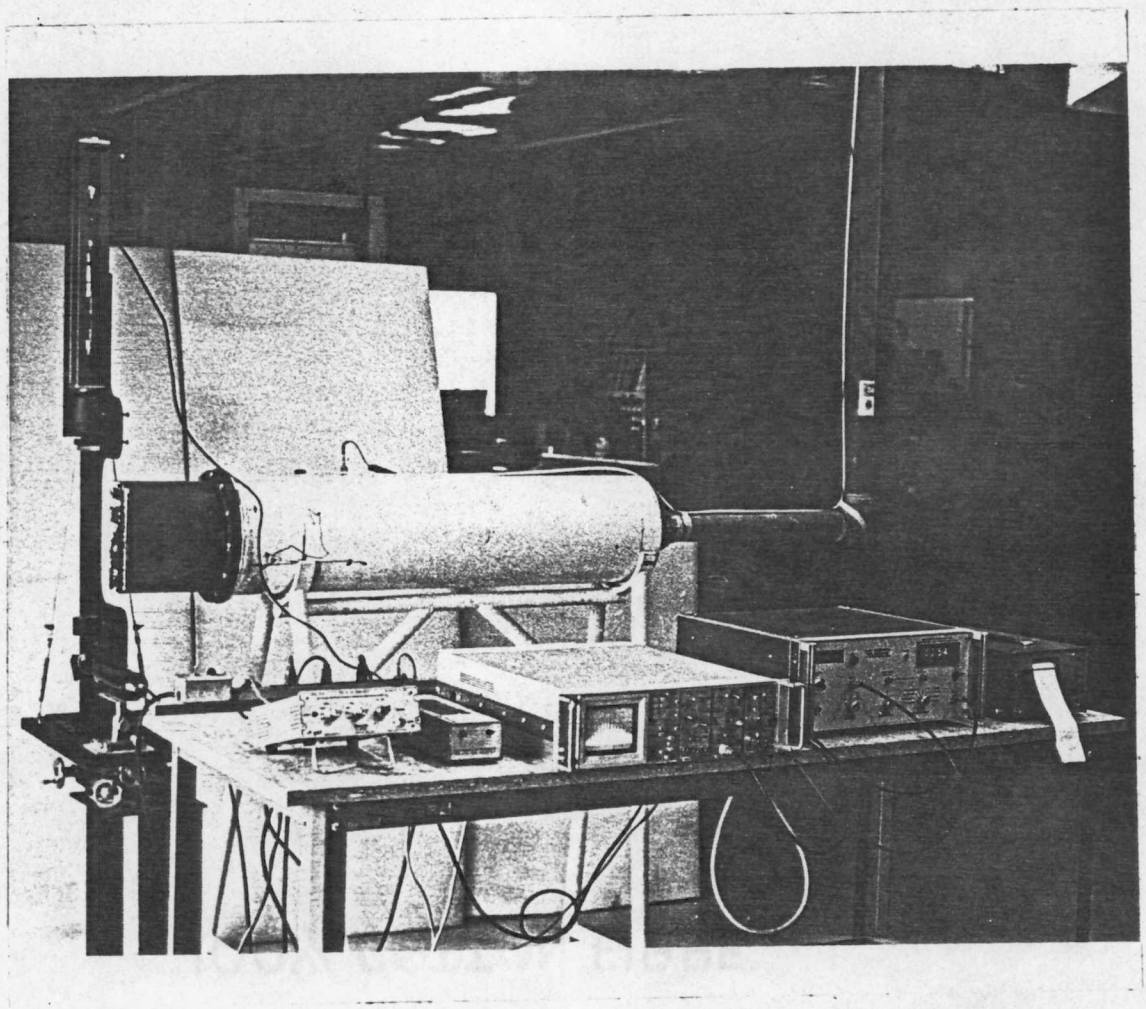


Figure 10. Photograph of Laser Velocimetry System

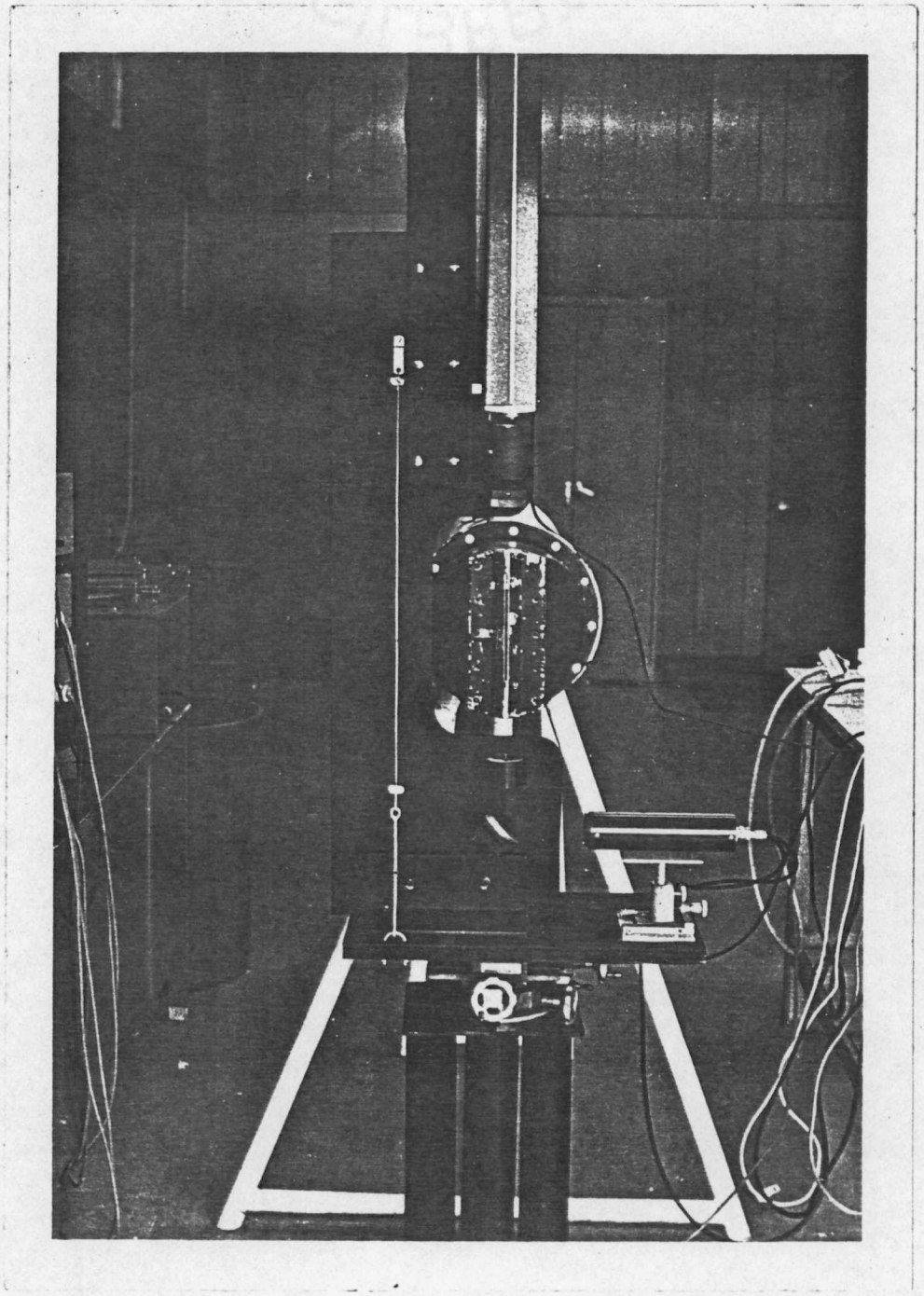


Figure 11. Photograph of Optics Portion of Laser Velocimetry System

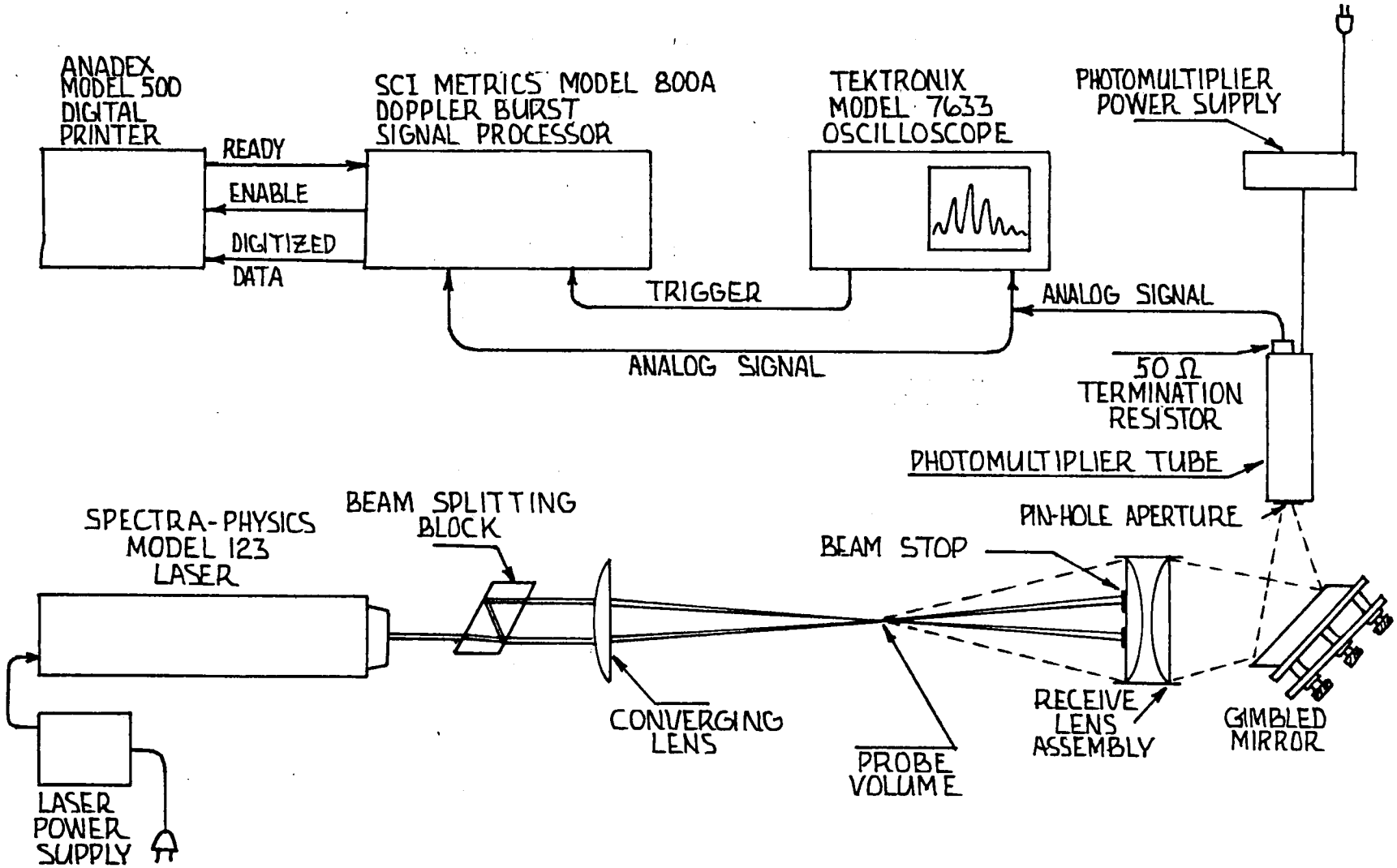


Figure 12. Schematic of Laser Velocimetry System

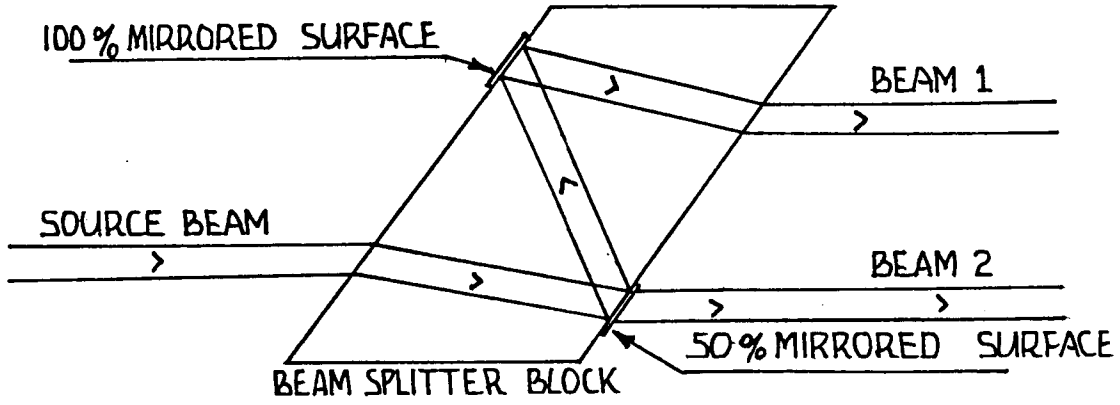


Figure 13. Illustration of Beam Splitter

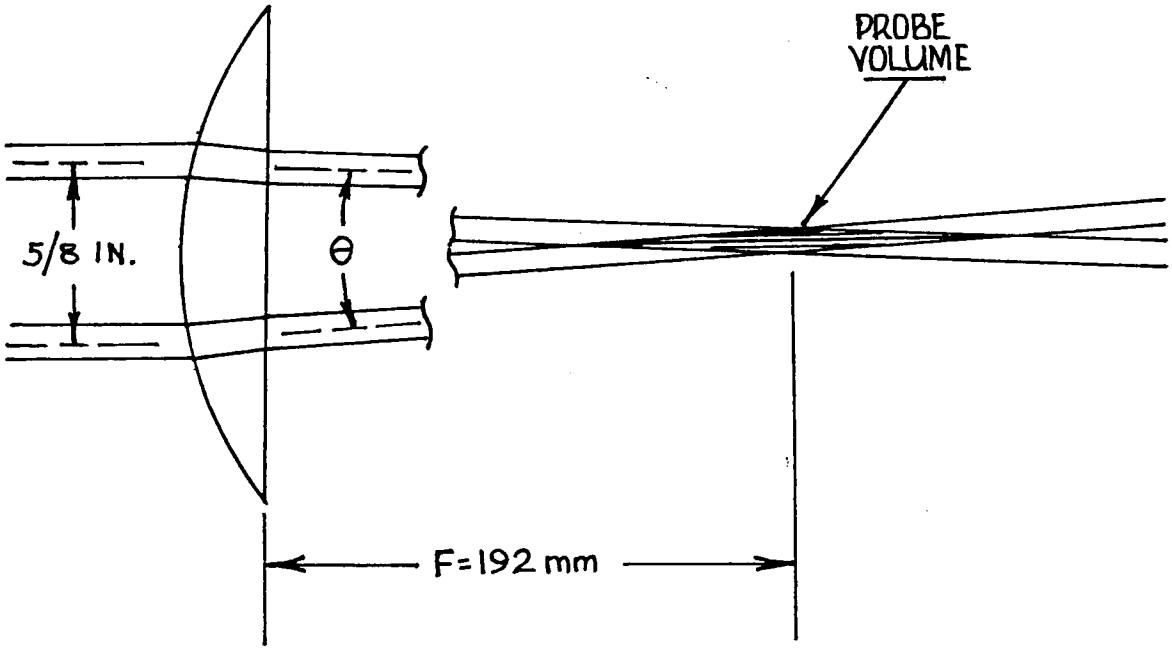


Figure 14. Illustration of Converging Lens and Incident Laser Beams

The angle θ was determined by projecting the beams on a wall approximately 50 feet beyond the beam intersection. The projection angles were adjusted such that the beams projected spots which were at a distance above the floor equal to the distance of the probe volume above the floor and the distance between the spots was minimum. The distance between the spots and the distance from the probe volume to the location equal distance between the spots on the line connecting the spots were measured. The ratio of one-half the distance between the spots to the distance from the probe volume to the wall was 0.037717 which equals the tan of θ/2. θ was thus determined to be 4.32 degrees.

Knowing the beams intersection angle, the $1/e^2$ beam diameter, and the converging lens focal length, we may calculate the probe volume dimensions. First from equation (13) we may calculate the $1/e^2$ beam diameter, $2a_o$, in the intersection area after passage through the converging lens.

Given equation (13)

$$2a_o = 4\lambda F/\pi 2a = 2\lambda F/\pi a$$

and

$$\lambda = 6.328 \times 10^{-4} \text{ mm}$$
$$F = 192 \text{ mm}$$
$$a = 0.45 \text{ mm}$$

Equation (13) becomes

$$2a_o = 0.171884 \text{ mm}$$

The probe volume dimensions follow from equations (14), (15), and (16) given θ=4.32 degrees.

Height, $h = 2a_o = 0.171884$ mm

Length, $l = 2a_o/\sin(\theta/2) = 4.56$ mm

Depth, $b = 2a_o/\cos(\theta/2) = 0.172$ mm

The fringe spacing in the probe volume, d, may be determined from

equation (9) given $\lambda = 6.328 \times 10^{-4}$mm and $\theta = 4.32$ degrees.

$$d = \lambda / 2 \, SIN(\theta/2) = 8.39476 \times 10^{-3} \text{ mm}$$

Knowing the probe volume depth and the fringe spacing, the number of fringes may be calculated from equation (17).

$$N = b/d = 0.172/8.39476 \times 10 \simeq 20$$

We have now characterized the probe volume of the laser velocimetry system. Note that the probe volume is much longer than it is high. The ratio of length to height is 26.53. This, of course, means that the spatial resolution of the system is much better in the two dimensions of the height and depth of the probe volume than in the dimension of its length. Many flow fields are essentially two-dimensional and spatial resolution in the third dimension is of little concern. This was the case with the air-jet nozzle for which the measurements were taken. It was a slot nozzle with an aspect ratio of 27.

The component following the converging lens was the receive optics assembly. The receive optics assembly consisted of two plano-convex lenses identical to the converging lens. The receive optics assembly was located such that the bisector of the angle formed by the two laser beams beyond the probe volume was orthogonal to the planar surfaces of the two lenses at their centers. This is the location for optimum system sensitivity. The planar surface of the first lens was orientated toward the probe volume at a distance of 192 mm, the lens focal length, from the probe volume. The lens diameter was 52 mm so the solid collection angle was 15.4 degrees. The second collecting lens was located in the same housing as the first with its convex surface orientated toward the convex surface of the first lens with a separation of approximately 1/4 inch.

Beam stops made from small pieces of opaque black tape were afixed to the front surface of the first collecting lens. This was necessary to prevent the beams from being projected into the aperture of the photomultiplier tube. The photomultiplier tube would be saturated and rendered insensitive to the scattered Doppler bursts if the beams were allowed to illuminate its photocathode.

Following the two collecting lenses was a front surface high reflectivity mirror mounted on three adjustable screws. The mirror surface was centered on the same axis as the two collecting lenses, but oriented at an angle of approximately 45 degrees to the axis. The purpose of the mirror was to allow easy alignment adjustments and project the image of the probe volume precisely on the pin-hole aperture of the photomultiplier tube. The distance to the mirror from the second collecting lens was approximately 64 mm or one-third the lens focal length.

Following the mirror was the photomultiplier tube. The pin-hole aperture of the photomultiplier was at a distance of approximately 128 mm from the center of the mirror surface. The diameter of the pin-hole was approximately 0.2 mm or just slightly larger than the height and depth of the probe volume. The photomultiplier tube was mounted on a track so that it could be moved slightly toward or away from the mirror to allow precise focusing of the probe volume image at the pin-hole.

To scatter an image of the probe volume for alignment of the receive optics assembly a small piece of vellum type drawing paper was held across the center of the probe volume length. The mirror was next adjusted to position the image just slightly to the side of the pin-hole. The photomultiplier tube was then moved to bring the image to a sharp focus. Finally, the mirror was adjusted to locate the image in the

pin-hole aperture. An eye loupe was necessary for making these adjustments at the pin-hole aperture.

The photomultiplier tube utilized was an RCA 8644. According to the tube specification, this tube has a quantum efficiency of approximately 5% at the 6328 Angstrom wavelength of the laser source. The tube's peak quantum efficiency is 18% at a wavelength of about 4000 Angstroms. The 5% quantum efficiency at 6328 Angstroms of the RCA 8644 is relatively high. Most photomultiplier tubes are even less sensitive to the red portion of the spectrum. This is the major disadvantage of helium-neon lasers in laser velocimetry applications. A green or blue laser source typically results in a much higher system sensitivity than that achieved with a red source.

The photomultiplier tube is a current device and must be terminated with a relatively low resistance to operate properly. The unit employed in the system herein described was terminated with a 50 ohm coaxial resistor which closely matched the characteristic impedance of the RG58 coaxial cable used to carry the output signal.

The output of the photomultiplier tube was connected to the inputs of an oscilloscope and an electronic Doppler burst signal processor. The oscilloscope used was a Tektronix Model 7633 storage unit with 50 megahertz response. The trigger level of the scope was adjusted so that it only generated a sweep when a Doppler burst was present on its input. The trigger output of the scope was connected to the trigger input of the electronic Doppler burst processor so that it only processed when the scope was triggered by an input signal.

The Doppler burst signal processor used was a Sci-Metrics, Inc. Model 800A. This processor operates in the frequency range of 15

kilohertz to 100 megahertz. Considering the probe volume fringe spacing of 8.39476×10^{-3} mm and utilizing equation (11) the minimum and maximum velocity which could be determined with the processor was 0.1259 meters/sec. and 839.476 meters/sec. respectively.

The Sci-Metrics Model 800A Doppler burst processor samples eight cycles of the input Doppler signal and digitizes the resultant time interval utilizing period counter techniques. The processor also tests the data pulse train for periodicity utilizing high speed digital computing circuitry. Time intervals of both four and five data pulses are compared to the time interval of eight data pulses. If the computed pulse periods differ more than a selected tolerance the signal is rejected. The comparison tests are carried out to prevent the logging of data which has been incorrectly measured. In the presence of low signal to noise ratio, signal pulse drop-out and pulse addition can occur due to noise interaction with the data signal. By comparing the measured period of the first four cycles, the first five cycles, and the total eight cycles aperiodic signals can be detected and rejected. The dual comparison test is utilized to prevent the acceptance of signals which might appear to be periodic when checked by only a single comparison, yet are in fact aperiodic.

The Doppler burst signal processor was connected to an Anadex Model DP-500 digital printer. The two are connected in "handshake" fashion so that they operated synchronously. The Doppler burst processor was disabled by a busy signal from the printer during a print cycle and enabled by a ready signal when the print cycle was complete. The print rate of the printer is 2.5 cycles per second. The Doppler burst signal processor can operate at a rate of several thousand samples per second. The print

rate of the printer thus limited the laser velocimetry system data acquisition rate to a maximum of 2.5 samples per second.

The Doppler burst processor and printer quantified and listed data as the time period between adjacent pulses in a Doppler burst data signal. In order to analyze the data, individual records had to be manually transferred to computer punched cards. The punched cards were then used to enter the data into a computer program which first converted the period measurement to velocity before statistically analyzing it. The computer program calculated the mean velocity and the standard deviation from the mean for a given group of samples.

CHAPTER III

APPLICATION OF THE LASER VELOCIMETRY SYSTEM IN THE AERO-ACOUSTICS LAB

After assembling the laser velocimetry system described in chapter two, research was conducted to determine its performance and suitability for employment as a flow analysis instrument in the Aero-Acoustics Lab. Various air-jet velocity measurements were taken and compared with theoretically predicted velocities as well as previously recorded hot-wire anemometry data. Data were also taken to determine the availability and aerodynamic characteristics of scatter centers in the lab air supply. In addition data were taken to determine the effect of laser power on the data acquisition rate of the laser velocimetry system at a given air-jet velocity. All measurements were made using a slot nozzle with a width of 5.1 mm and length of 137.7 mm.

The first series of measurements were made with the probe volume located at the geometric center of the slot at a distance of 15.3 mm or three slot widths downstream of the nozzle exit. The probe volume was oriented so that its long dimension, ℓ, paralleled the slot nozzle length and the component of velocity measured was the axial component. Measurements were made with nozzle exit Mach numbers of 0.32, 0.5, 0.7, 0.9, and 0.95. Several hundred data points were collected at each velocity and a histogram was plotted of these measurements. Figure 15 on the following page is this histogram plot. Note from Figure 15 that the measured velocity distribution are centered very near the predicted velocity up to a Mach number of 0.7. Above this velocity the measurements fall

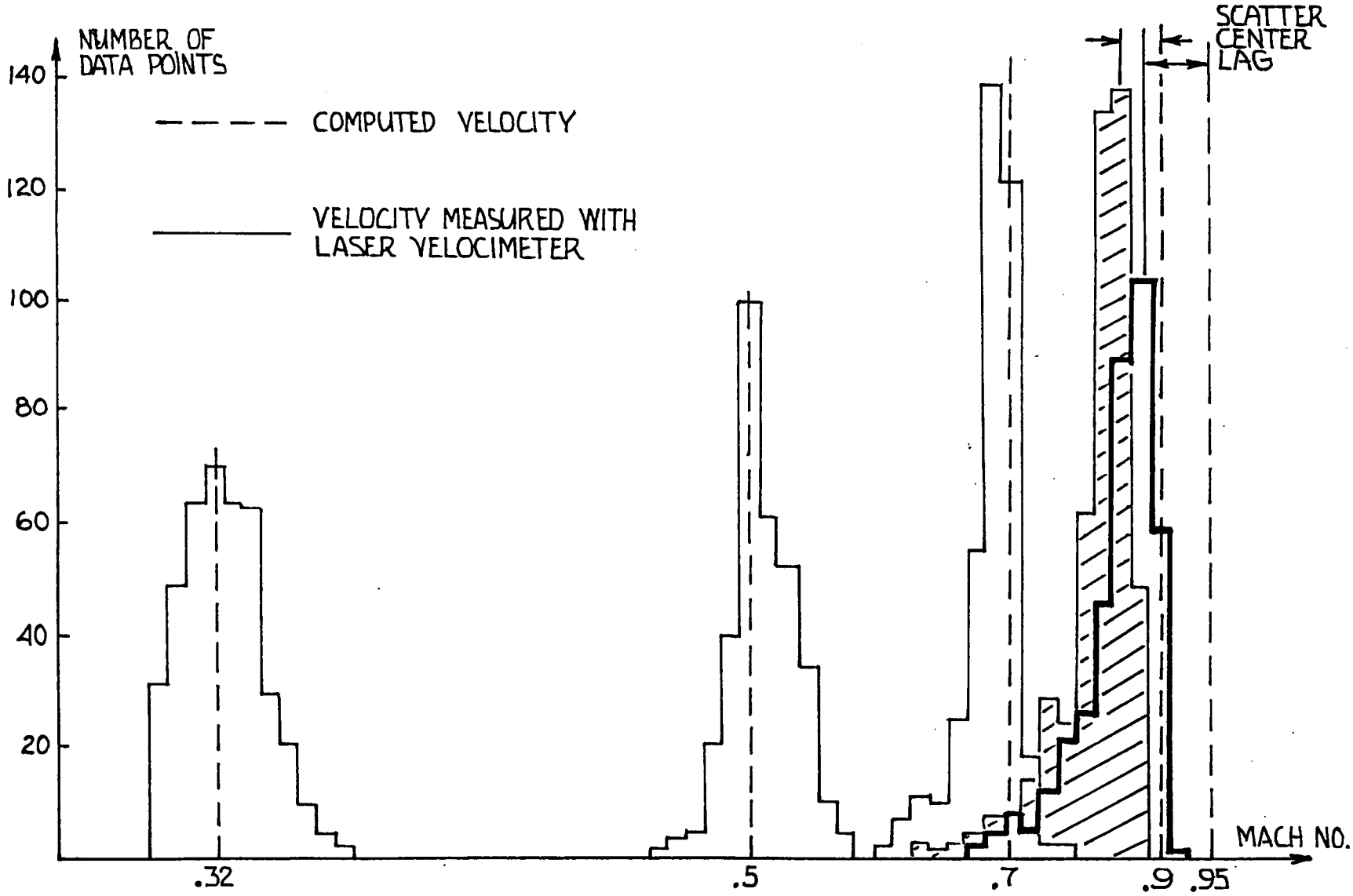


Figure 15. Histogram Plot of Data Collected at Different Velocities

increasingly below the predicted velocity. This was due to the scattering centers lagging the air flow at the higher velocities. From this data it was concluded that the laser velocimetry system was suitable for use in the Aero-Acoustics Lab with inherently available scattering centers up to a velocity of Mach number equal to 0.7 in non-turbulent flows.

This series of tests was conducted at peak laser power of 5.6 mW. A study was then conducted to determine the effects of laser power on the data acquisition rate and on the measured velocity for a given location and flow condition. With the probe volume centered on-axis and five slot widths downstream measurements were made at nozzle exit velocities of Mach number equal to 0.32, 0.5 and 0.7. Laser power was varied at each velocity from 0.5 mW to 4.0 mW utilizing a polaroid filter. Measurements were taken at 0.5, 1.5, 2.0, 2.5 and 4.0 mW laser power in the probe volume. Figure 16 illustrates variation in the data acquisition rates versus laser power.

As can be seen the data acquisition rates were similar at the different velocities for a given laser power. This result was not expected since more scatter centers per unit of time traverse the probe volume at higher velocity. Therefore a higher data acquisition rate was expected at higher velocity. At higher velocity the scatter centers have shorter residence time in the probe volume. Fewer photons are thus scattered and the resultant scattered signal intensity is lower. It must be concluded that the loss of usable signals due to lower intensity must have offset the increase in the total number of scatters put unit of time at higher flow velocity.

Figure 17 illustrates the observed effects of laser power on the measured velocities. This plot was made using fifty discrete measurements

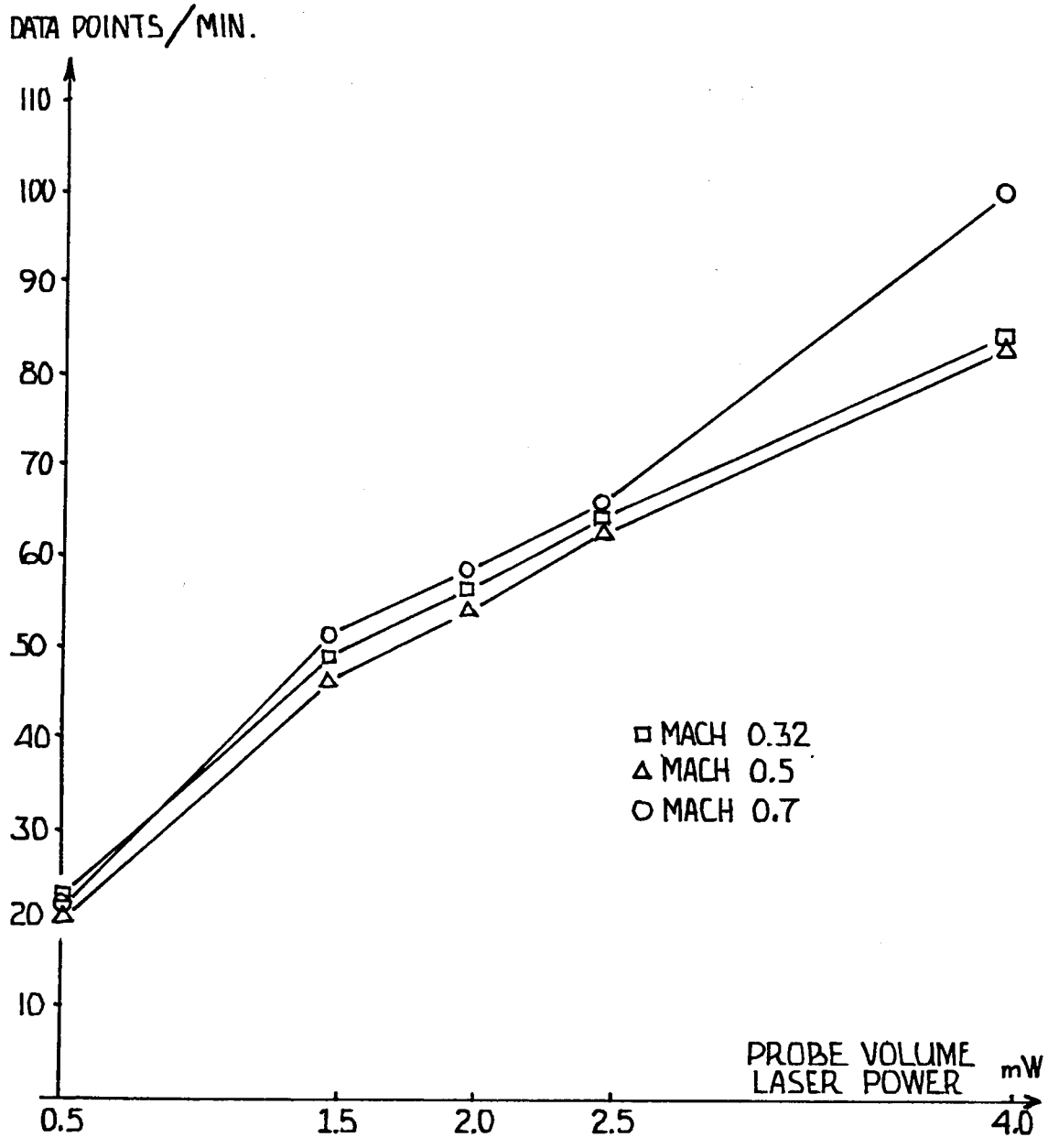


Figure 16. Plot of Data Acquisition Rate Versus Laser Power

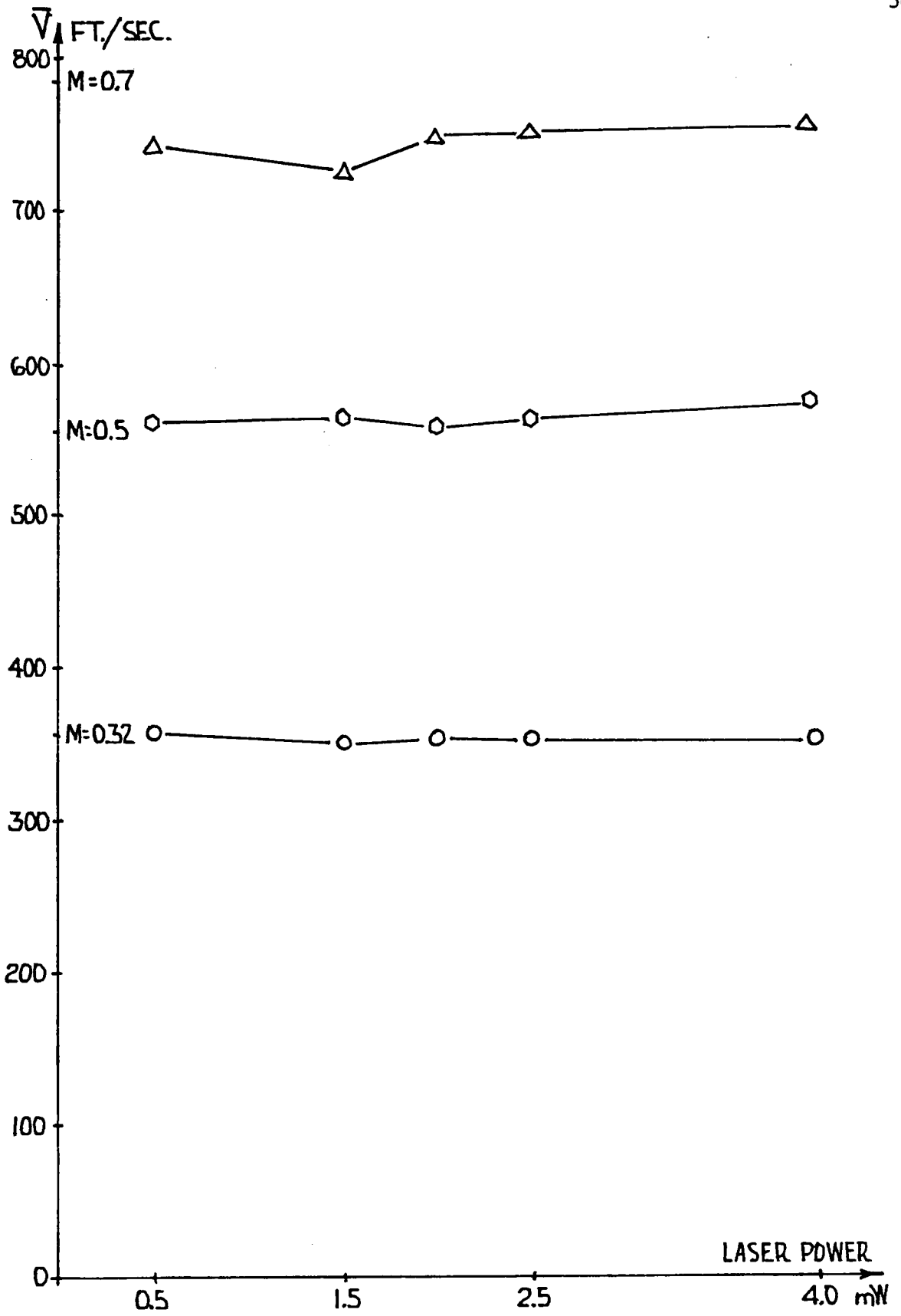


Figure 17. Plot of Measured Velocity Versus Laser Power

at each condition. As can be seen no significant variation in measured velocity was noted with variation in laser power. From this result it must be concluded that the great majority of scatter centers available in the air supply have similar aerodynamic or flow following characteristics in the range of velocities investigated. As shown in Figure 16 the data acquisition rate decreased with a decrease in laser power. Thus signals from some of the available scatter centers were not detected due to low intensity. The signals being lost must have been from smaller scatter centers which were less efficient optical scatters. These same scatter centers would be expected to be better flow followers than larger scatter centers. This, however, must not have been the case.

The fact that the inherently available scatter centers in the lab air supply appear to have similar aerodynamic characteristics is very good from the standpoint of laser velocimetry application. For surely the accuracy of both velocity and turbulence measurements must be enhanced when the flow following characteristics of the scatter centers are not greatly varied.

Following this study two cross sectional velocity and turbulence intensity profiles were recorded for the slot nozzle. Both profiles were recorded at nozzle exit velocity of Mach number equal to 0.32. The first profile was taken at a location 3 nozzle slot widths downstream, the second at 10 slot widths downstream of the nozzle exit. The profiles were accomplished by first locating the probe volume at the center-line or axis of the nozzle. The probe volume was then moved outward in small increments. At each stop several hundred data points were collected from which the mean velocity and turbulence intensity were determined. These profiles were half profiles of a symmetric flow field. Figures 18 and 19

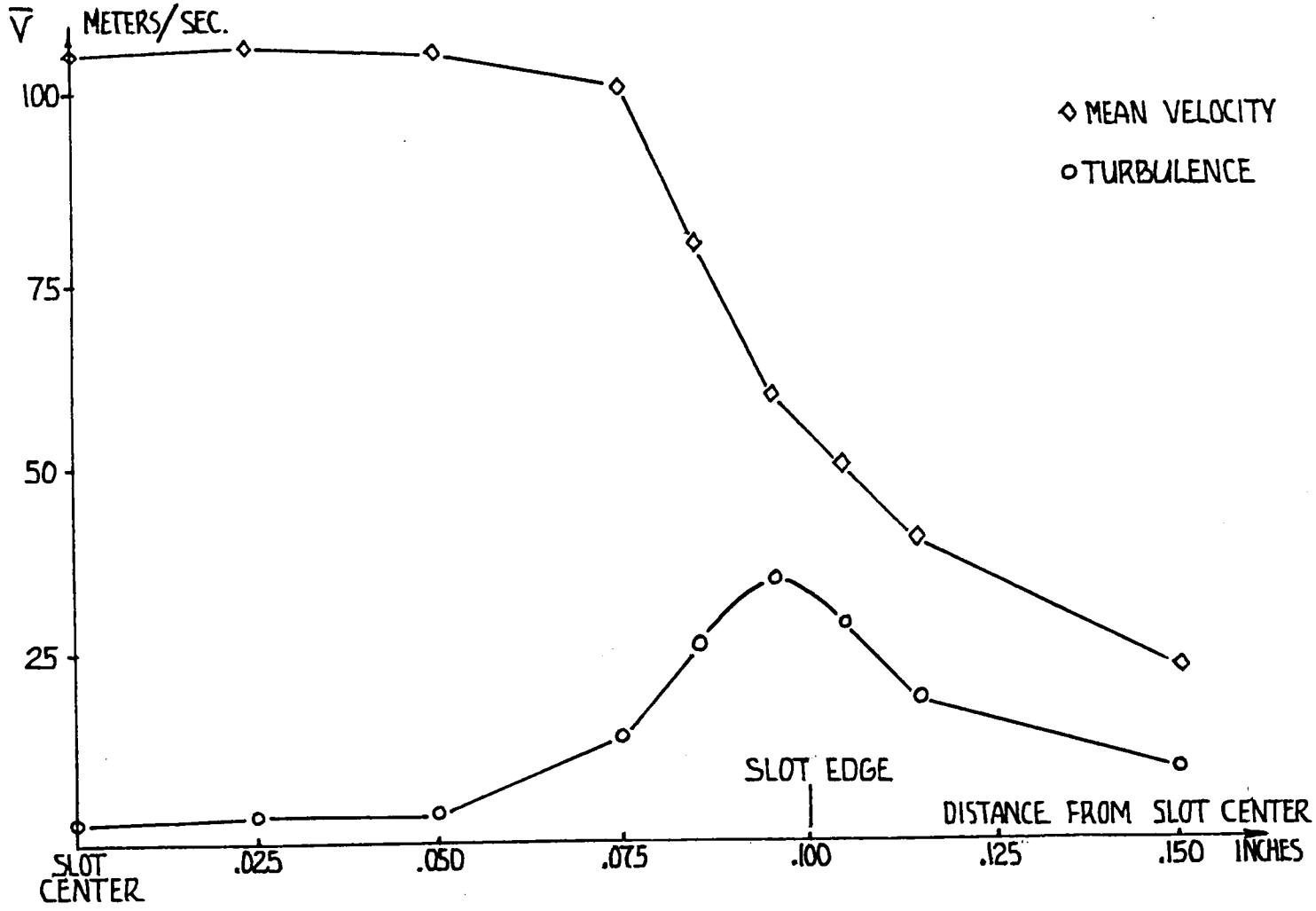


Figure 18. Velocity Profile of Slot Nozzle as Measured by the Laser Velocimetry System with Probe Volume Located Three Slot Widths Downstream

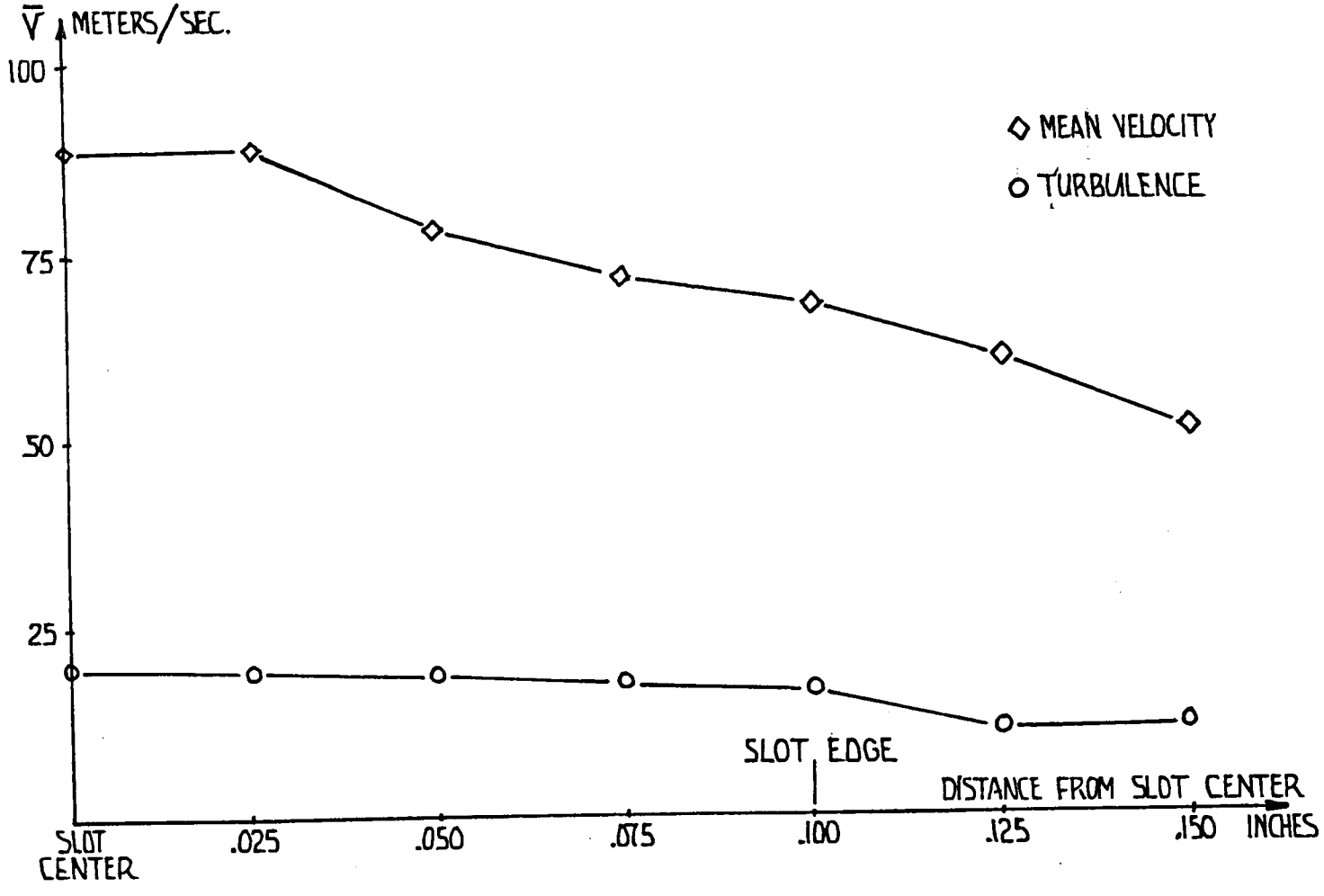


Figure 19. Velocity Profile of Slot Nozzle as Measured by the Laser Velocimetry System with Probe Volume Located 10 Slot Widths Downstream

illustrate the results of these measurements.

These profiles compare favorably with previously obtained hot-wire anemometry profiles. Figure 20 is a replot of Figure 18 with results of a hot-wire profile superimposed. The hot-wire data represents the magnitude of the velocity while the laser velocimetry data is the single component of velocity along the nozzle axis.

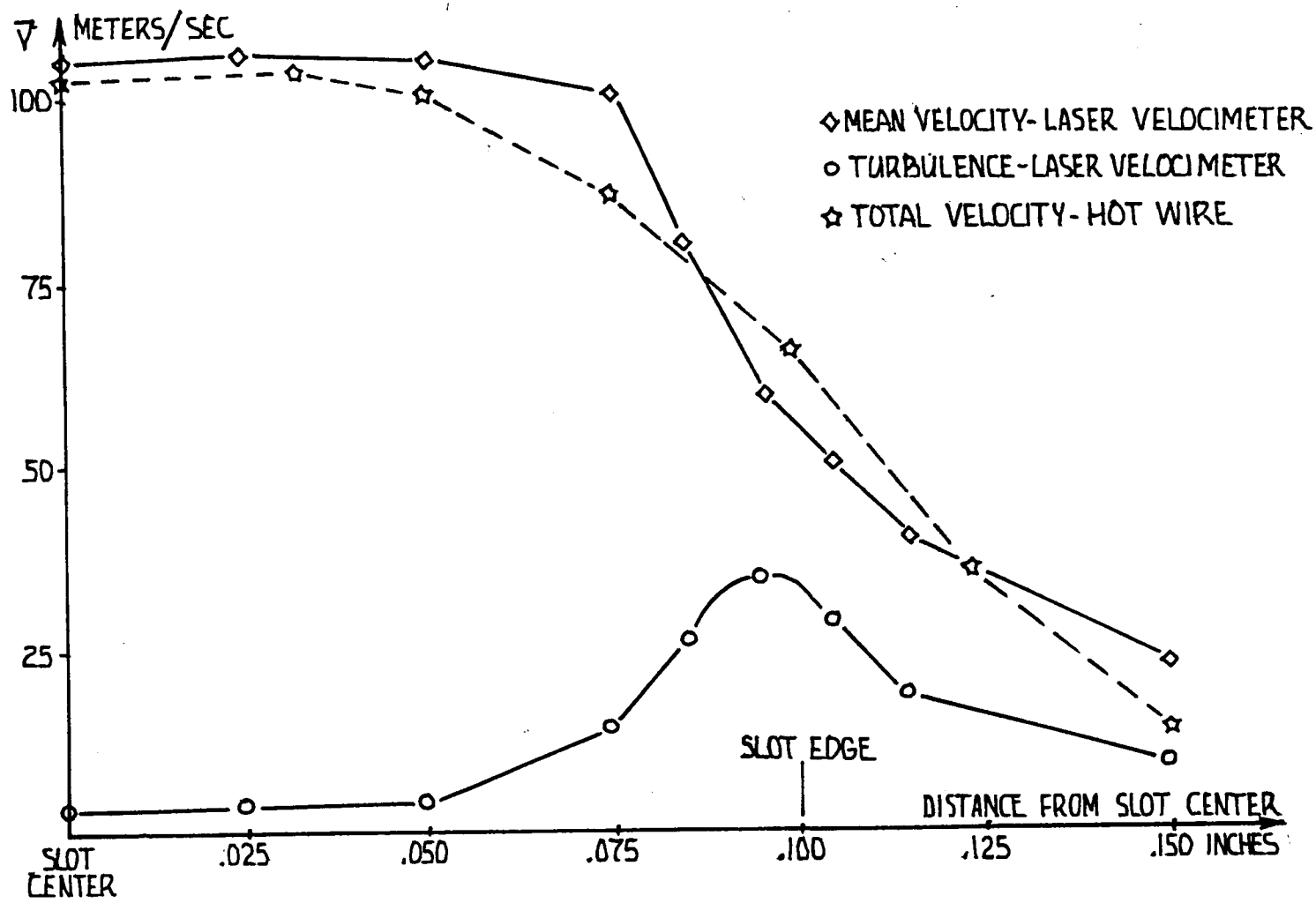


Figure 20. Velocity Profile Plot Comparing Laser Velocimetry Data with Hot-Wire Data

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that the employment of a laser velocimetry system in the UTSI Aero-Acoustics Laboratory for air-jet flow analysis is feasible and would enhance the flow analysis capability of the laboratory. Measurements could be made in higher velocity flows than previously analyzed by hot-wire techniques in our laboratory. The flow fields could also be analyzed from the standpoint of flow directionality by measuring individual components of velocity.

The laboratory air supply was shown to inherently carry optical scatter centers suitable for laser velocimetry application. These scatter centers were shown to have good flow following characteristics up to near Mach 0.7 and to have similar flow following characteristics within the range of velocities studied.

The laser velocimetry system developed and utilized for this study was limited in its measurement capability. For actual analysis work a more sophisticated system should be considered. Desirable improvements include higher sensitivity, faster data logging rate and added processing capabilities, directional sense, and a two components of velocity measurement capability.

Higher sensitivity could be readily achieved by simply changing the laser source to green or blue instead of red. Photomultiplier tubes are much more responsive to the green or blue portions of the spectrum than to the red.

Higher data logging rate and processing capabilities could be

achieved by obtaining a micro-computer system. The computer system could very rapidly store data on magnetic floppy disk and retrieve and process off-line after a given measurement is complete. With high sensitivity and fast data logging, higher turbulence frequencies could be resolved. Also the time required to make a given measurement would be reduced.

Adding directional sense to the laser velocimetry system would require shifting the optical frequency of one of the laser beams prior to the probe volume. This is usually achieved by passing the laser beam through a transparent medium in which acoustic traveling waves are propagating. Devices called acoustic Bragg cells are commonly utilized for this purpose. The Bragg cell splits the incident beam into two beams one of which is shifted in frequency by an amount equal to the frequency of the traveling wave. When these two beams are converged to intersection they form a probe volume with moving interference fringes. The moving fringes allow for a determination of the direction through which a scatter center traverses the probe volume.

Finally, adding a second component of velocity to the measurement capability of the laser velocimetry system would greatly enhance its use as a flow diagnostics instrument. By simultaneously measuring both velocity components of a two-dimensional flow field the flow velocity may be completely defined. A two component laser velocimetry system may be constructed by using a two-dimensional Bragg cell to split an incident laser beam into three secondary beams. If the three beams are then properly converged to intersection a probe volume will be formed with two sets of orthogonal fringe planes. The two-dimensional Bragg cell provides for shifting two of the secondary beams by different frequencies. This allows measurements to be separated into directional components.

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APPENDIX

APPENDIX

LISTING OF COMPUTER PROGRAM USED FOR PROCESSING DATA

```
   N=(insert number of measurements being processed)
   READ(5,1) (TAU(I), I=1,N)
   DO 13 I=1,N
   V(I)=(1.0/TAU(I)*CON
   WRITE(6,2) I,V(I)
 2 FORMAT(1X,' V( ',I3,' ) = ',F10.6)
13 CONTINUE
   YT=0.0
   DO 11 J=1,N
   YT=YT+V(J)
11 CONTINUE
   VBAR=YT/N
   TOT=0.0
   DO 12 K=1,N
   TTOT=(V(K)-VBAR)**2
   TOT=TOT+TTOT
12 CONTINUE
   TURB=SQRT(TOT/(N-1))
   WRITE(6,3) VBAR,TURB
 3 FORMAT(' VBAR = ',F10.6,10X,'TURB = ',F10.6)
 1 FORMAT(10F7.3)
   STOP
   END
```

VITA

James E. Winchester was born in Brownsville, Tennessee on March 7, 1947. He attended public schools in that area. He attended Tennessee Technological University and participated in their Co-operative Education Program. His work assignment was with ARO, Inc., contract operator of the Arnold Engineering Development Center. He received a Bachelor of Science Degree in Electrical Engineering in June of 1971. He then enlisted in the United States Navy and was commissioned an Ensign in November of 1971 following which he served aboard the USS Trenton (LPD-14) as Communication Officer until August of 1974. He entered the University of Tennessee Space Institute in September of 1974. He later received employment with ARO, Inc. where he remained until November of 1978. He is presently employed as an Instrumentation and Controls Engineer by the Energy Conversion Division of the University of Tennessee Space Institute.