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HARDWARE AND SOFTWARE INTEGRATION FOR CONCURRENT DATA ACQUISITION AND REDUCTION OF PHOTON CORRELATED LASER DOPPLER VELOCIMETRY

THESIS

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HARDWARE AND SOFTWARE INTEGRATION FOR CONCURRENT DATA ACQUISITION AND REDUCTION OF PHOTON CORREELATED LASER DOPPLER VELOCIMETRY

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air Training Command
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by
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Captain USAF
Graduate Astronautical Engineering

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Preface

Laser Doppler Velocimetry has become widely accepted and utilized as a technique for studying turbulent fluid flow. Experiments using the equipment have historically been tedious and time consuming in the processing of the large quantities of information generated. This process can be greatly streamlined by employing an Automatic Data Acquisition System to perform the routine tasks of electronic equipment control, data transfer and recording, and computations. Integrating the two systems provides an experimenter with greatly increased capability to conduct large scale real time turbulence studies.

My study was sponsored by the Air Force Flight Dynamics Laboratory, under the auspices of Dr. N. G. Nagaraga. The effort has produced a system that will be beneficial to the laboratory in future fluid dynamic studies, allowing experimenters to concentrate on the results of studies, rather than on the techniques necessary to obtain results.

My deepest gratitude extends to my thesis advisor, Dr Harold E. Wright for his continual patience and encouragement. His dedication to education brought me from fledgling apprentice to practicing magician, able to perform miracles under less than ideal conditions.

This thesis would not have been possible without the support, devotion and loving care from my dear wife Suzie, and B. H. Rudolph. Their sacrifice and understanding through this period was more than I can ever repay.

David L. Neyland

Contents

Contents

List of Figures

List of Figures

List of Tables

Symbols

Fd -- unshifted frequency of photon signal (Hertz)

Fdp -- doppler frequency of photon signal (Hertz)

Frequency -- frequency of the phase modulator (Hertz), positive for drive mode, negative for inverted

G1 -- autocorrelation value at the first valley of the autocorrelation curve

G2 -- autocorrelation value at the peak immediately following the first valley (G1)

G3 -- autocorrelation value of the second valley

Ln -- focal length of the focusing lens (meters)

Nn -- number of interference fringes in the control volume at the intersection of the laser beams

PI -- numeric value of pi (3.14...)

Pk2 -- Digital Correlator channel number corresponding to the peak represented by G2

R -- decay ratio of the autocorrelation curve

Ro -- radius of laser beam control volume, assumed the same as the laser beam radius (@ 0.00055 meters)

Se -- laser beam spacing at the focusing lens (meters)

Sp -- interference fringe spacing (meters)

St -- Digital Correlator sample time (seconds)

Ti -- computed turbulence intensity (percent)

Two0 -- the included angle between the laser beams at their point of intersection (radians)

U -- computed velocity (meters/second)

Ud -- uncorrected velocity indicated by doppler signal (meters/second)

Wv -- wavelength of the laser used (6.328 E-07 meters)

ABSTRACT

A general Automatic Data Acquisition System dedicated to a broad range of experiments is used to operate the Digital Correlation signal processing equipment of a Laser Doppler Velocimeter, transfer data from the correlator into the Automatic Data Acquisition System computer and perform computations with the information. The Laser Doppler Velocimeter is used to acquire vast quantities of velocity and turbulence intensity information describing turbulent fluid flow about two dimensional airfoils. Integration of the Velocimeter with the computer increases the capability of the system to perform large scale fluid dynamic studies.

The necessary electronic interfaces, control functions and computational software were developed to provide a fully operational computerized laser velocimetry system while avoiding the exclusive dedication of a sophisticated computer to the experiment. The system was tested during actual experimental operations to validate the techniques employed. Data was collected in an experiment examining the effects of constant area mixing ducts with ducted ejector airfoils. Results of the computational techniques employed herein were validated by separate manual effort conducted by other experimenters.

HARDWARE AND SOFTWARE INTEGRATION FOR CONCURRENT DATA ACQUISITION AND REDUCTION OF PHOTON CORRELATED LASER DOPPLER VELOCIMETRY

I. INTRODUCTION

Laser Doppler Velocimetry offers a method of unobtrusively studying complex fluid dynamics. Applied to aerodynamic fluid flow experiments, this optical technique provides direct measurements of fluid velocity and turbulence characteristics. Electro-optical observations of free moving particles in a fluid flow system are made possible by the interference patterns formed by the intersection of twin laser beams. Modern electronic signal processing equipment evaluates the doppler signal pattern of light reflected from a particle moving through the laser interference fringe region. Mathematical analysis of the signal reveals the velocity and turbulence of the flow field.

Previous Work. As early as 1964 Yeh and Cummings (Ref 21) were conducting the first experiments with what is now commonly referred to as a Laser Doppler Velocimeter or a laser anemometer. In the ensuing years techniques and applications of Laser Doppler Velocimetry have flourished, with considerable effort having been spent to substantiate the accuracy of Laser Doppler Velocimetry results as compared with other anemometry methods. At the Air Force Institute of Technology and at Air

Force laboratories at Wright-Patterson Air Force Base, work has been completed by Catalano, Cerullo, Morris, Rogers and Walterick (Refs 6, 7, 13, 16 and 20), wherein Laser Doppler Velocimetry was used to measure turbulent fluid flow concurrently with measurements made by hot-wire anemometers and Prandtl-type pitot static tubes. Laser Doppler Velocimetry has repeatedly proven an invaluable tool for gathering otherwise difficult to obtain data on fluid flow in free streams, laminar boundary layers and turbulent mixing regions.

Current Work. Concurrently with the work described in this thesis, experiments were performed to study the turbulent flow field about an ejector wing design incorporating a constant area mixing duct. This experiment was conducted by Captain D. G. Stephens in partial fulfillment of the degree of Master of Science at the Air Force Institute of Technology. The experiment relied exclusively upon a Laser Doppler Velocimeter to gather considerable quantitative flow information. The shear magnitude of data required in such an experiment, as well as the extremely time consuming data collection and reduction procedures necessary, prompted this present attempt to apply the capabilities of an Automatic Data Acquisition System to aid Laser Doppler Velocimetry experiments. The goals of the present study are to reduce the tedium of data collection, improve real time evaluation of turbulent flow and provide for long term evaluation of experimental data while avoiding the exclusive long term dedication of a sophisticated computer to the process.

Present Study. The scope of this effort is to develop the essential hardware and software to fully integrate the Automatic Data Acquisition System with the Laser Doppler Velocimeter. The objectives of the study are to:

1. Design, prototype, test and build the necessary electronic interfacing equipment to provide for control of the Laser Doppler Velocimeter Digital Correlator Signal Processor by the Automatic Data Acquisition System and to provide for data transfer from the Laser Doppler Velocimeter Digital Correlator to the Automatic Data Acquisition System.
2. Develop, implement and test software to control the Laser Doppler Velocimeter Digital Correlator Signal Processor, to transfer data from the Laser Doppler Velocimeter Digital Correlator to the Automatic Data Acquisition System, to perform velocity and turbulence calculations with the data, and to provide for long term data management, storage and retrieval.
3. Maintain the autonomy and independence of the Automatic Data Acquisition System by utilizing non-permanent interfacing techiques which do not require physical modifications to the computer and ensure that the computer is free to be used in

other experiments and need not be exclusively dedicated to the Laser Doppler Velocimeter.

This thesis deals with these objectives and will also include an operational description of the test environment, the Laser Doppler Velocimeter and the Automatic Data Acquisition System, a discussion of examples of the type of information produced by the integrated system and a presention of the theoretical background on Laser Doppler Velocimetry techniques.

II. Aerodynamic Fluid Flow Test Facility

The test apparatus in which the Laser Doppler Velocimeter was used to measure aerodynamic fluid flow was the Air Force Institute of Technology "Blue Smoke Tunnel" (Fig 1) located in Laboratory Room 142, Building 640 at the Air Force Institute of Technology School of Engineering. This unique smoke tunnel has an interesting history in itself, originally designed and built by the Germans and subsequently liberated by the Americans after World War Two, brought to the United States for aeronautical research, and eventually donated to the Air Force Institute of Technology. The tunnel was resurrected and modified in 1959 by Baldner (Ref 3) in his Master's Thesis project.

The smoke tunnel provides for observing two dimensional fluid flow in an open ended system capable of subsonic incompressible velocities up to 23 meters/second. The air flow is pulled through the tunnel by two diffuser isolated fans, each driven by a 1.5 horsepower electric motor. The free stream air flow velocity is continuously monitored by a Prandtl type pitot static tube connected to a microanemometer.

Extreme care was taken in the design and modification of the tunnel to control and eliminate turbulence in the fluid flow. The air inlet to the tunnel is a bell mouth of 0.2 meters radius of curvature in order to correct the concentration ratio of 11.5 to 1. Directly inside the bell mouth is a screen section of honeycomb construction, 0.076

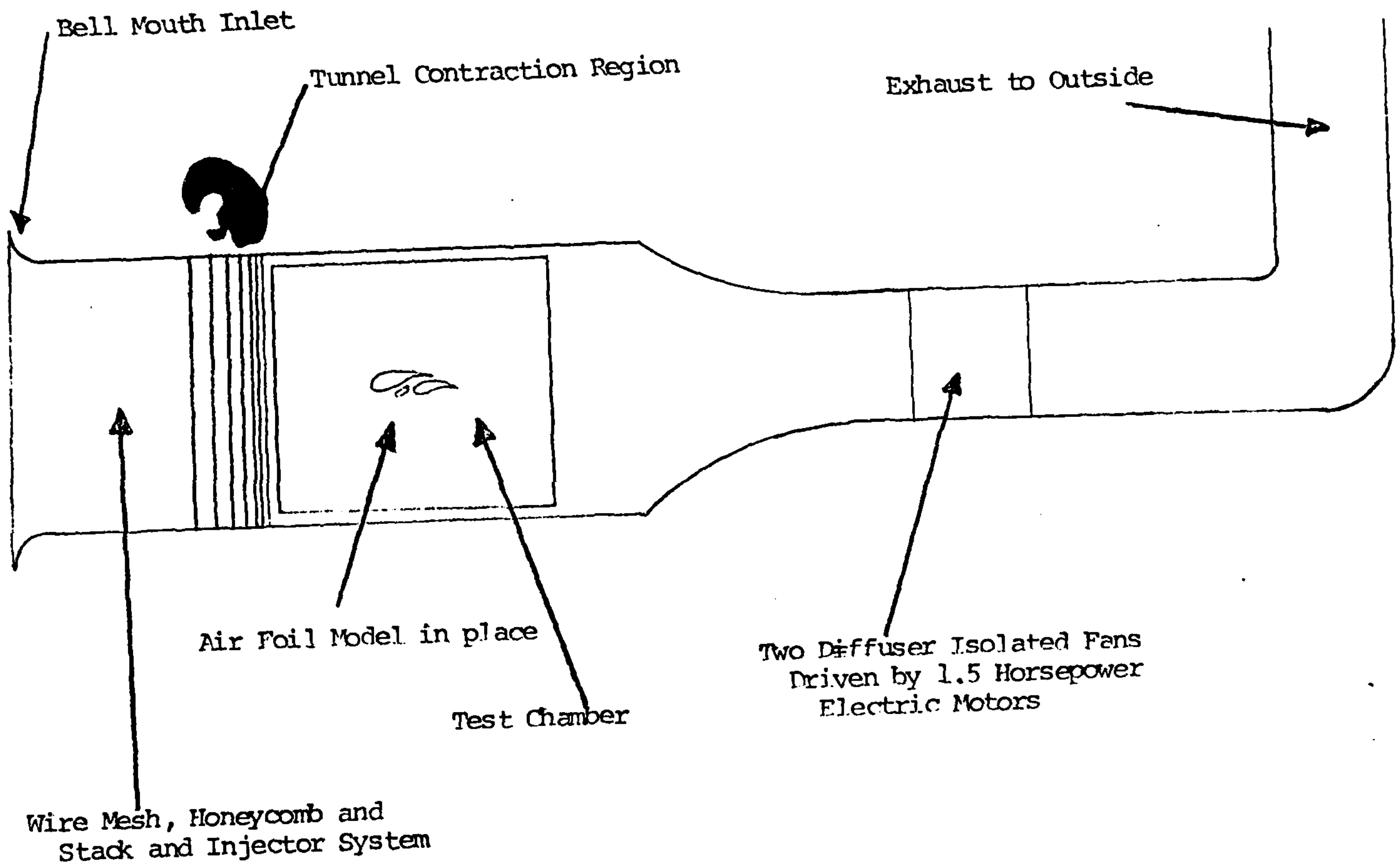


Figure 1 Air Force Institute of Technology "Blue Smoke Tunnel"

meters thick, with a length to diameter ratio for the openings of eight. The honeycomb serves to break up large turbulent fluid structures before they enter the tunnel. Downstream of the honeycomb are a series of finer and progressively finer screens to break up the smaller turbulent structures, up to the point of the stack and injector system used to introduce smoke particles into the moving fluid.

Flow visualization in the Air Force Institute of Technology Blue Smoke Tunnel is created by thin stream tubes of flow marker smoke in the fluid flow. These stream tubes of smoke are produced by the stack and injector apparatus in the tunnel contraction region. The airfoil shaped stack has sixty-five 0.006 meter (inside diameter) injector tubes emerging from the trailing edge of it. The marker particles injected into the fluid flow from the injector tubes are kerosene smoke droplets. The kerosene smoke is generated by two 900 watt inconel heaters boiling off kerosene fuel at 605 degrees Kelvin. The kerosene vapor is mixed under pressure and turbulent conditions with cool air, forming a dense, white, non-corrosive and non-toxic smoke. The smoke passes through a condensing chamber to eliminate water vapor before it flows to the stack and injector apparatus, there to enter the free stream of the tunnel. Measurements in the free stream indicate that there may be as much as a 1% turbulence in the smoke stream tubes due to the stack and injector design of issuing secondary flow into the mainstream of the tunnel.

The heart of the smoke tunnel is the flow visualization region. It is a transparent test section, 1.5 meters long and 1.0 meter high. The test section is 0.076 meters thick and has removable front sections of 0.0097 meter thick plexiglass, plate glass and other suitable materials. The back wall of the test section is laminated plate glass.

The design of the smoke tunnel is optimum for using Laser Doppler Velocimetry in the backscatter mode, wherein the laser device and the photon collecting device are on the same side of the tunnel (Ref 6).

III. Laser, Interface and Computer Equipment

The equipment employed in this study falls into three general categories, the Laser Doppler Velocimeter, the interface and the Automatic Data Acquisition System. The Laser Doppler Velocimeter consists of a laser, a beamsplitter, a phase modulator, a photomultiplier tube, a digital correlator signal processor and an oscilloscope. The interface includes two standard input/output devices and a voltage translator. The Automatic Data Acquisition System includes a computer with a cathode ray tube display and two disk drives.

A. Laser Doppler Velocimeter (Fig 2).

1. Laser. The laser utilized in this procedure is a 15 milliwatt helium neon laser, Spectra Physics Model 124A, accompanied by a Model 255 DC Exciter. The laser produces a single monochromatic beam of coherent light at 6328 angstroms wavelength, appearing bright red. The beam has a diameter of 0.0011 meters, characterized by the gaussian beam profile and 1/(e^2) intensity radius.

2. Beamsplitter (Fig 3). Attached to the front of the laser is a Malvern Instruments RF307 transmitter beamsplitter and polarizer. The device utilizes prismatic optics to divide the single beam from the laser into two parallel, equal intensity beams. The

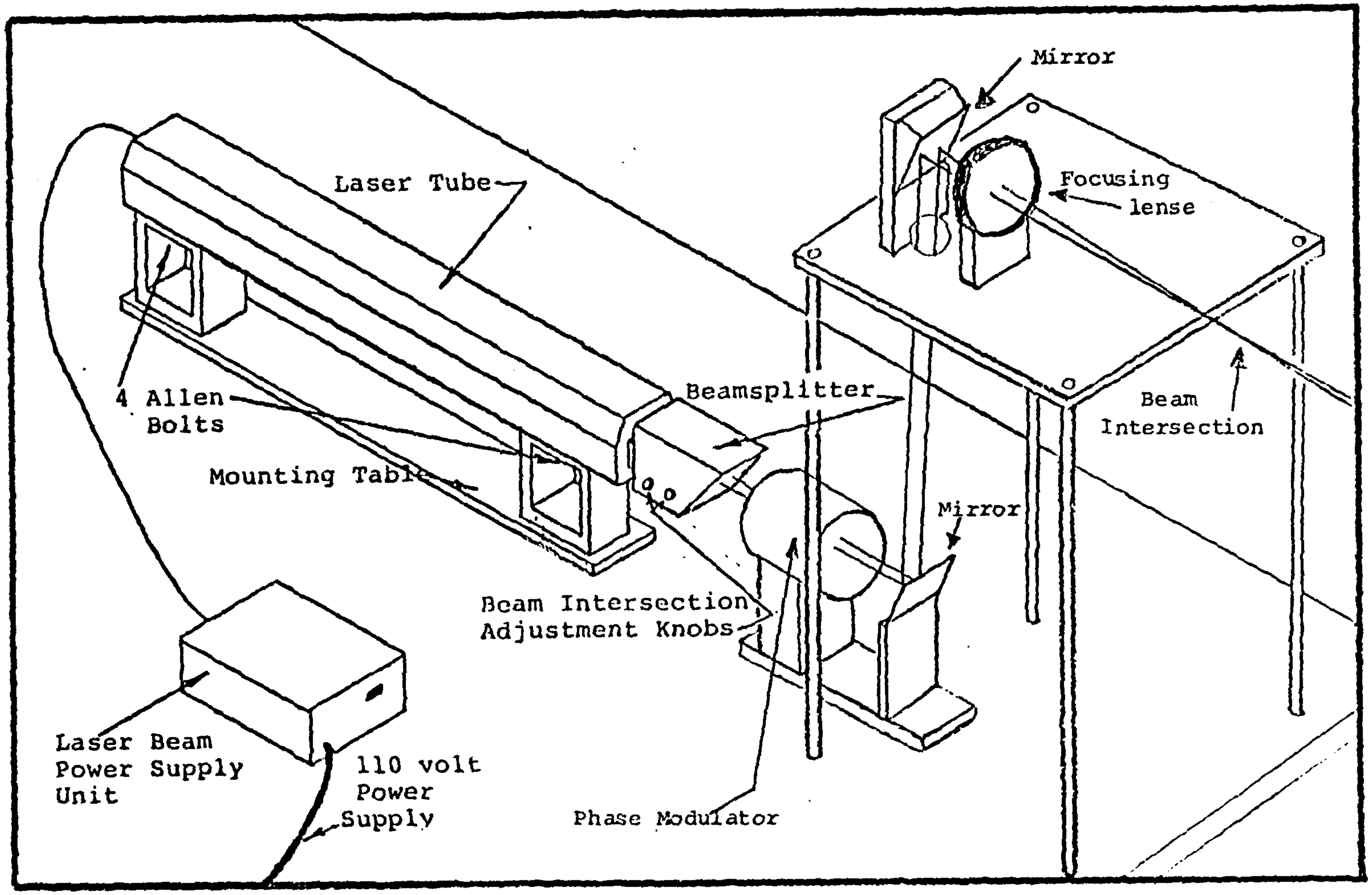


Figure 2 Laser Doppler Velocimeter Physical Layout

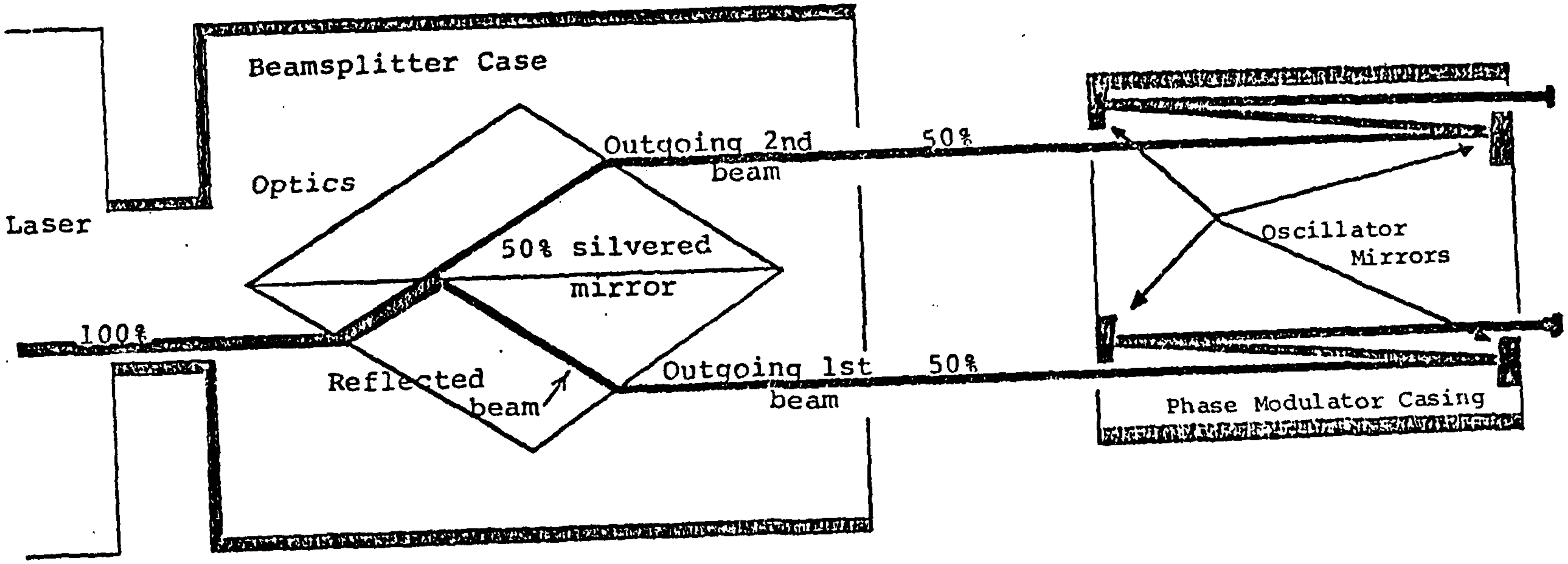


Figure 3
Beamsplitter and Phase Modulator Operation

polarizer can be used to eliminate horizontally or vertically polarized components of laser light. The pair of beams leaving the beamsplitter are identically 0.0011 meters in diameter and spaced apart a variable, but controllable distance. Two controls on the side of the beamsplitter casing adjust the internal prisms to vary the beam spacing and their parallel nature upon exiting the device.

3. Phase-Modulator (Figs 3 and 4). An optional phase modulation unit may be placed in the optical path of the laser beams from the laser to the aerodynamic test chamber. In use it provides a method of introducing a doppler frequency shift to the laser fringes produced by the intersection of the twin laser beams in the test chamber. This is useful in cases of high turbulence intensity, or high speed flow, wherein the Laser Doppler Velocimeter may not be able to sense the direction of the fluid flow. The phase modulator causes the fringe pattern to move either with or against the fluid flow direction and proper signal interpretaion produces a valid estimate of fluid velocity and turbulence intensity. The particular

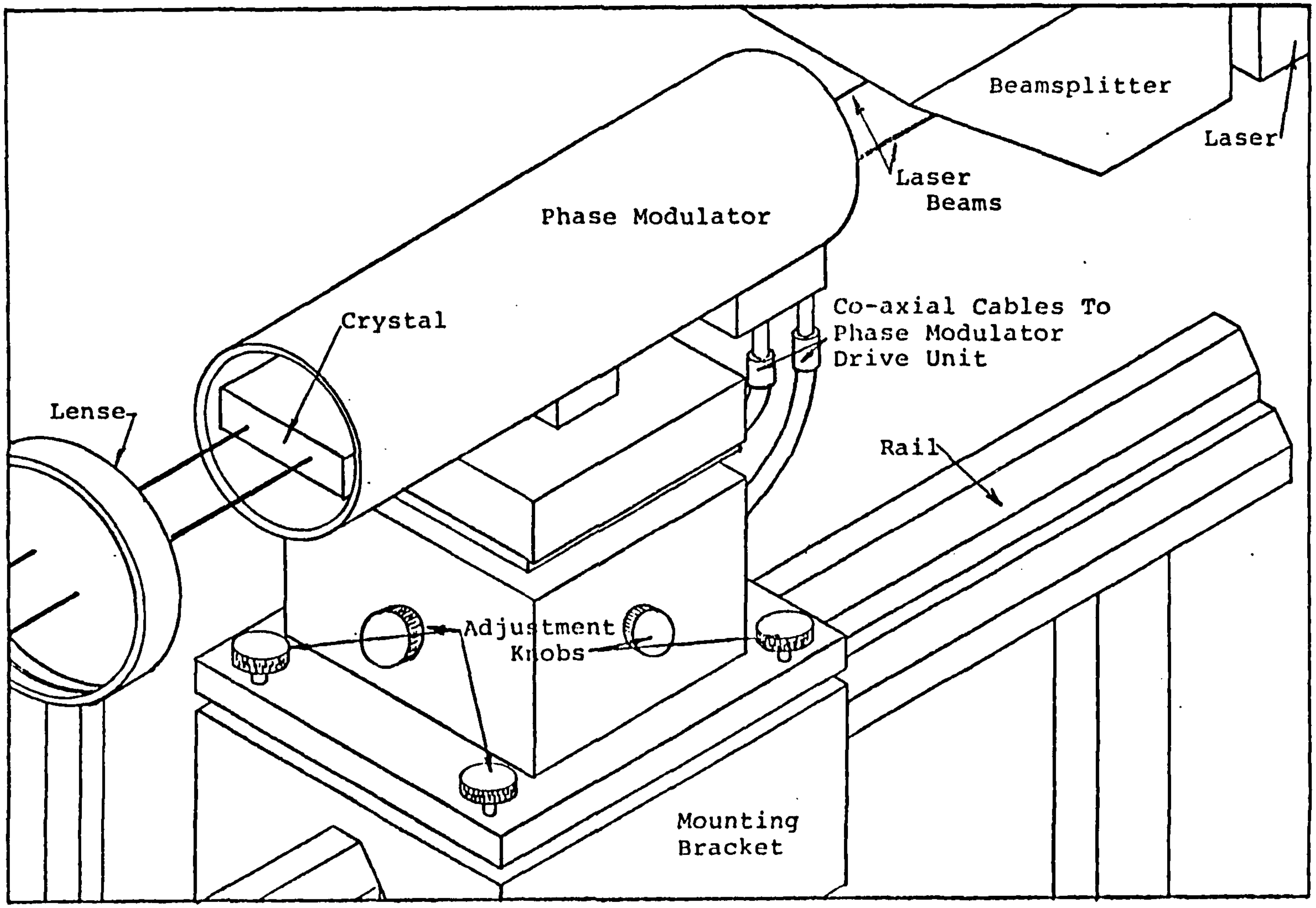


Figure 4 Phase Modulator Placement in Optical Path

Phase Modulator used is an Electro Optic Developments PC-14 Light Modulator, with two pizeo-electric optical crystals optimized for the wavelength of the laser. Oscillation of the crystals by the Malvern Instruments K-9023 Laser Anemometer Phase Modulation Drive Unit causes the optical path length for each of the twin laser beams to change as a function of time, with respect to each other. This introduces a doppler frequency shift to the fringe pattern in the test chamber. The exact frequency of the doppler shift is necessary in calculating the velocity and turbulence of the fluid flow in the test chamber and is measured by a Hewlett-Packard 5325B Universal Counter.

4. Photo-Multiplier Tube (Fig 5). The photon detection element in this Laser Doppler Velocimeter is an EMI 9863 Model KE/100 Photo-Multiplier tube from Malvern Instruments. On the front of the tube is a Tamron f2.5, 105 millimeter multi-coated lens, which focusses light and photons from the test chamber into the Photo-Multiplier tube. The point of focus of the lens must be adjusted to coincide exactly with the intersection of the twin laser beams in the

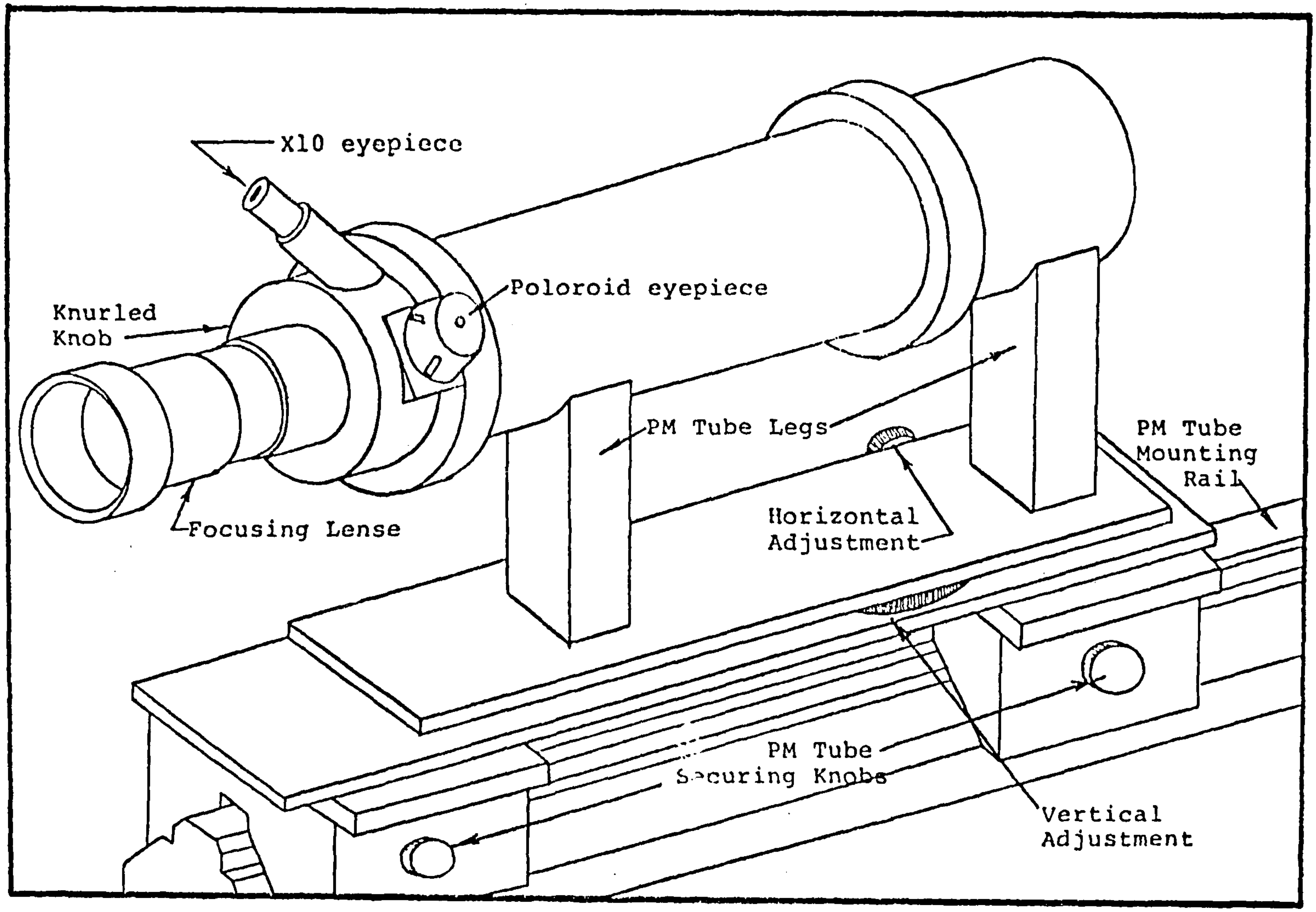


Figure 5 Photo-Multiplier Tube

test chamber, in order to focus the fringe pattern onto the pinhole aperture of the Photo-Multiplier tube. The tube is exceptionally sensitive to light and can be operated only under extremely subdued lighting conditions. The tube is powered by an EMI power regulator tuned to its particular characteristics. The power supply provides a constant 1850 volts for the cathode of the tube during its operation.

5. Digital Correlator (Fig 6). The heart of the Laser Doppler Velocimetry system is the signal processing system. This system uses a Malvern Instruments K7023 Digital Correlator and Storage unit, accepting continuous signals from the Photo-Multiplier and producing an autocorrelation function. The correlator continuously processes the signal and displays a real-time representation of the information on an oscilloscope hooked up to its output. The correlator has facility for electronic input control functions to clear the storage, start and stop the correlation function, and electronically read out the data in digital form as Binary Coded Decimal digits.

6. Oscilloscope (Fig 6). A Tektronics 425

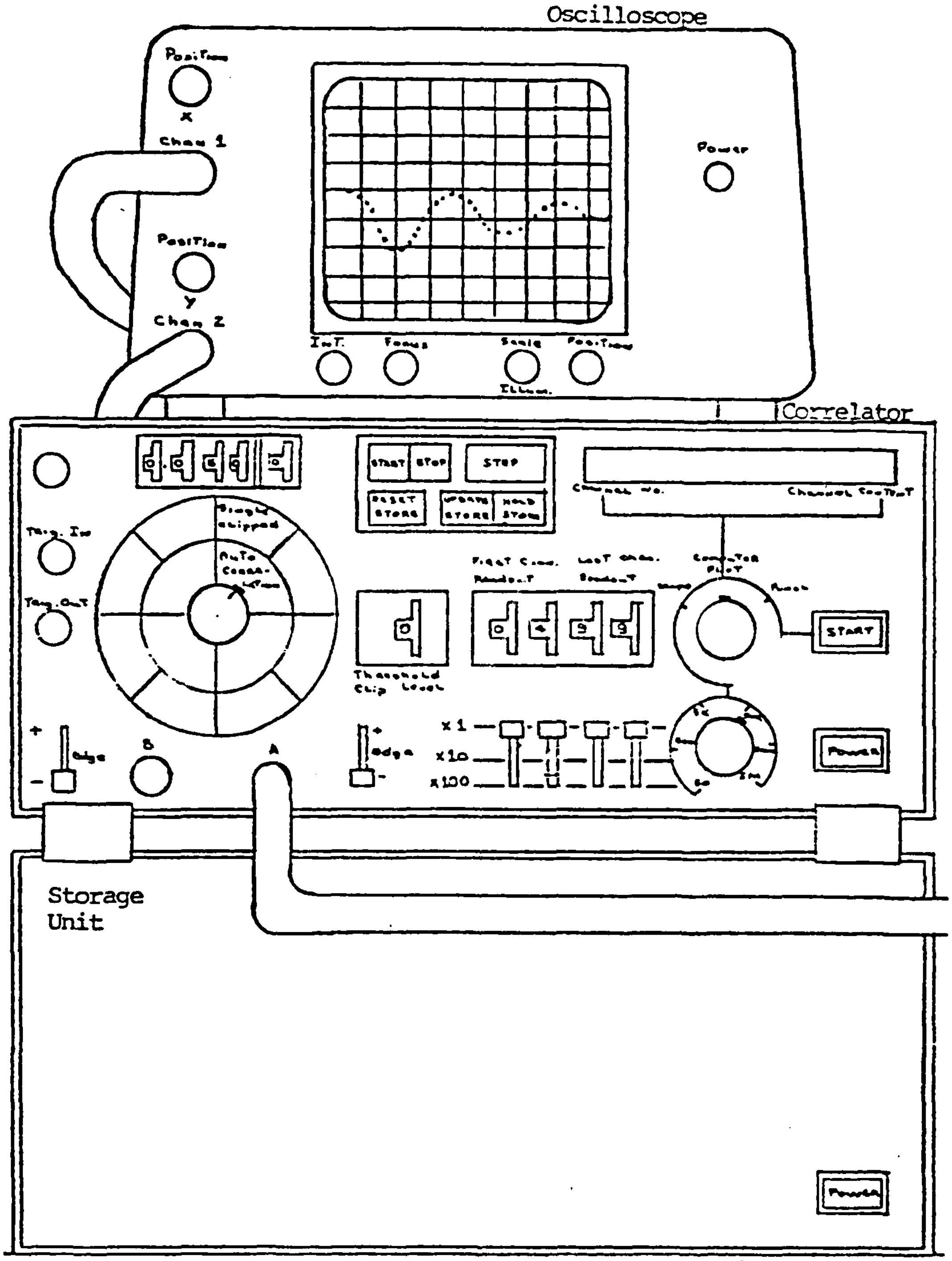


Figure 6 Digital Correlation Equipment

oscilloscope with z-axis control is connected to the display output of the digital correlator. The oscilloscope is used to view a real-time representation of the autocorrelation function.

B. Electronic Interfaces.

Two standard, off-the-shelf interfaces were used in this research. They can either be plugged into the expansion ports of the computer as indicated below, or into the port of a Hewlett-Packard 9874A Input/Output expander, whose own interface is then connected to the computer expansion port.

1. The Hewlett-Packard 98032A Input/Output Interface is a general purpose interface providing two-way, 16-bit data exchange between the Automatic Data Acquisition System and the Laser Doppler Velocimeter. The input and output data and control lines are all separate and independent. It can perform input and output simultaneously. The output function is used in this project and is controlled by the Hewlett-Packard Basic binary write statement, "WRITEBIN" which outputs a single, binary, 16-bit number. This number is interpreted by a voltage translation circuit which in turn outputs to the Digital Correlator the proper voltage

signal and thereby performs the remote control functions.

2. The Hewlett-Packard 98033A BCD Interface provides the Automatic Data Acquisition System with the capability to extract Binary Coded Decimal information from the Laser Doppler Velocimeter using this bit-parallel, digit-parallel output method. This method transfers all four data bits of all eight digits simultaneously. This is a uni-directional communication device, transferring output data from the Digital Correlator into the computer.

C. <u>Automatic Data Acquisition System</u>.

This research is centered around use of a standard, unmodified computer system. A description of the components is included to clarify the general capabilities of the computer.

1. Computer (Fig 7). The computer system is based around a Hewlett-Packard 9845B computer with a built-in cathode ray tube display, thermal printer, two tape drives and an extended keyboard.

   a. Cathode Ray Tube Display. The cathode ray tube is capable of displaying 80 characters horizontally. The display is the primary means by which the computer

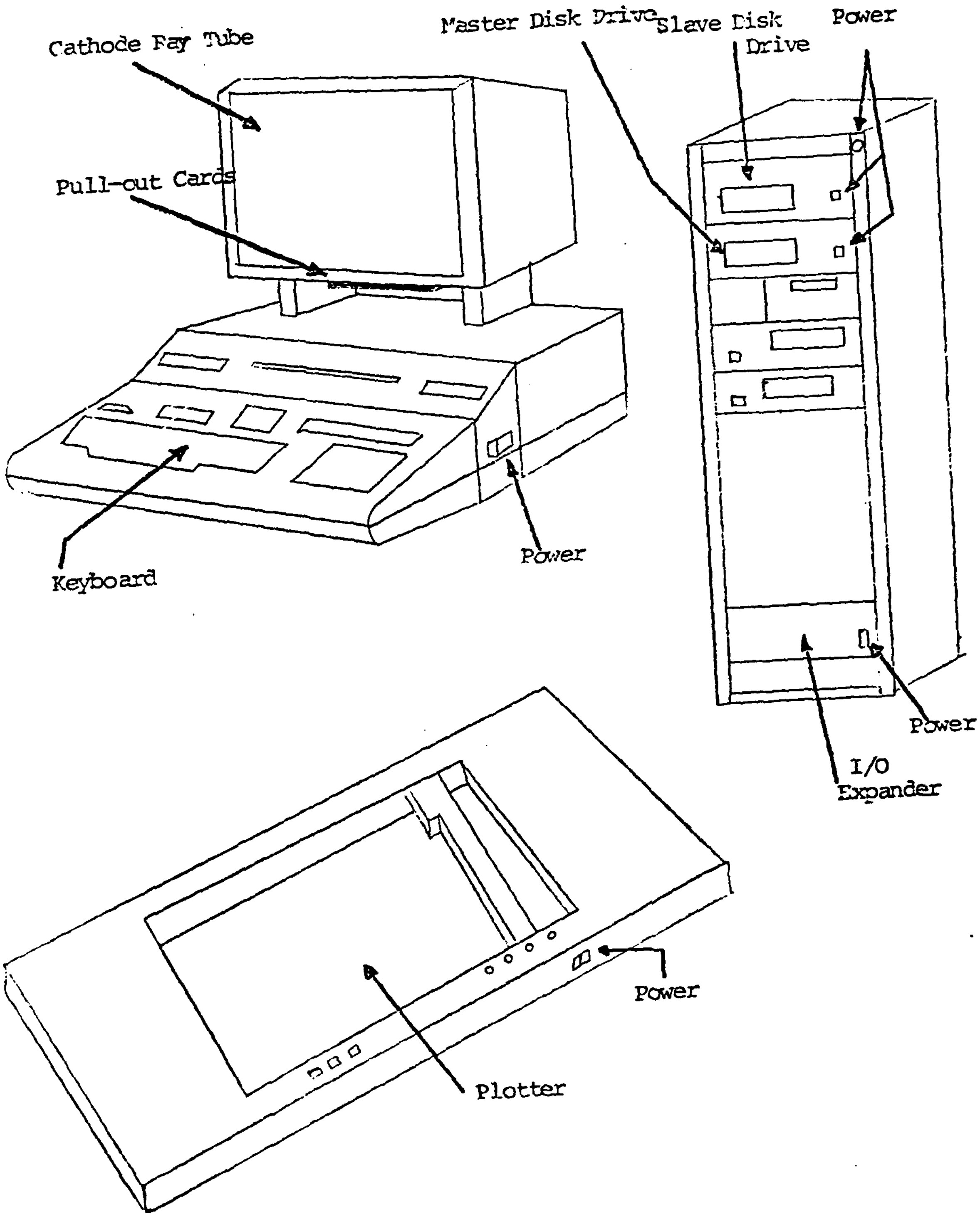


Figure 7 Hewlett-Packard 9845B Computer

communicates with a user and is used for editing programs or reports such as this one, viewing data or graphical plots, examining results and receiving error messages. It is functionally subdivided into twenty lines of printout area, a single line for input and output messages, two lines for viewing characters input from the keyboard and a system comment line for displaying error messages and results from numerical calculations.

b. Internal Thermal Printer. Built into the front of the computer is an eighty character thermal line printer for hard copy output. Any display on the cathode ray tube may be printed on the thermal printer. It can also be used to produce hard copies of program listings, data, results from program execution or graphical plots.

c. Internal Tape Drives. Two magnetic cassette cartridge tape drives are located in the front of the computer. They can be used for storage and retrieval of programs and data used in the computer. An individual tape can hold up to 216,832 bytes of information.

d. Extended Keyboard. The primary means for a user to communicate with the computer is through the keyboard built in to the computer. The keyboard is organized similarly to a standard typewriter keyboard, but contains sixty extra keys. Sixteen of these keys are located in the upper right hand corner of the keyboard, labled K0 through K15. These are the computer softkeys. They are used to control program execution by causing internal computer interrupts, allowing a user to manually manipulate the flow of a particular program. In the center of the keyboard are nine keys containing up, down, left and right arrows. The arrows cause the blinking cursor on the display to move around, but are also used to move and pinpoint locations on the graphics display.

e. Read Only Memory (ROM). The computer is equiped with several read only memories which store predefined functions and programs used internally by the computer. These read only memories include a Graphics ROM to allow program execution of plotting commands, an I/O ROM expanding the computer's capability for execution of input and output functions, and a Mass Storage ROM which permits use of a disk drive system with the computer.

f. Read/Write Memory. The computer is equiped with a total of 318,026 bytes of read/write memory, also known as random access memory. This is the main working area of the computer, used for program and data storage.

g. Pull-Out Cards. Under the front of the cathode ray tube are four pull-out cards. The cards contain details explaining computer error messages which appear on the cathode ray tube, as well as instructions on some operationg procedures for the computer.

h. Expansion Ports. On the back of the computer are four expansion ports, receptacles for plugging in various interfaces which may be connected to the computer. Utilizing interface cards connected to these ports, the computer can communicate with other electronic devices and peripherals.

i. Real Time Clock. A battery operated, quartz crystal oscillator clock can be connected to one of the expansion ports of the computer. The clock's battery is charged whenever the computer power is turned on, but retains an accurate date and time over extended periods of battery operation. The clock also contains several timers and interrupt devices which can be preset by computer programs and later cause interrupts at desired intervals. The date and time information are continuously available for reading into the computer by a set of simple Hewlett-Packard Basic commands.

2. Disk Drives. Two Hewlett-Packard 9885 disk drives are connected to the computer, one of which is a Master unit and the other a Slave. Each unit operates independently in terms of data storage and retrieval and can store up to 499,200 bytes of information on removable individual flexible disks. The disk drives are on average twenty-five times faster in operation than the computer's internal tape drives, and significantly faster still when reading and writing random access data

storage files.

3. Plotter. A Hewlett-Packard 9872S plotter is connected to the computer. It can produceplots in four colors interactively or under program control. It can also be used to digitize information for input to the computer from a predrawn graph or picture.

IV. Principles of Laser Doppler Velocimetry

General Background. There are basically two types of Laser Doppler Velocimetry that have been experimented with over the past few years (Ref 11). The most popular and extensively used method is the dual scatter or fringe system. It has an excellent signal to noise ratio and can be used either in a forward-scatter or back-scatter mode (Fig 8), increasing its adaptability to varying wind tunnel environments. The second type is based upon using a reference laser beam along with a single scattering beam. As the dual scatter or fringe system is far superior and alone is used in this procedure, the reference beam system will not be mentioned further in this thesis.

Laser Doppler Velocimetry has many advantageous features (Ref 4). It is an entirely non-obtrusive technique of measuring aerodynamic fluid flow. Laser Doppler Velocimetry uses no physical probe to be inserted into the flow field, leaving the region of interest completely undisturbed. This is radically different from techniques such as hot-wire or hot-film anemometry, or Prandtl type pitot static tubes. In addition Laser Doppler Velocimetry measures the velocity and turbulence intensity directly, independent of temperature and pressure, and eliminating the need for the complex recurrent calibration that is required by other methods. Laser Doppler Velocimetry offers very good spatial resolution, allowing measurements to be made near walls and other surfaces with

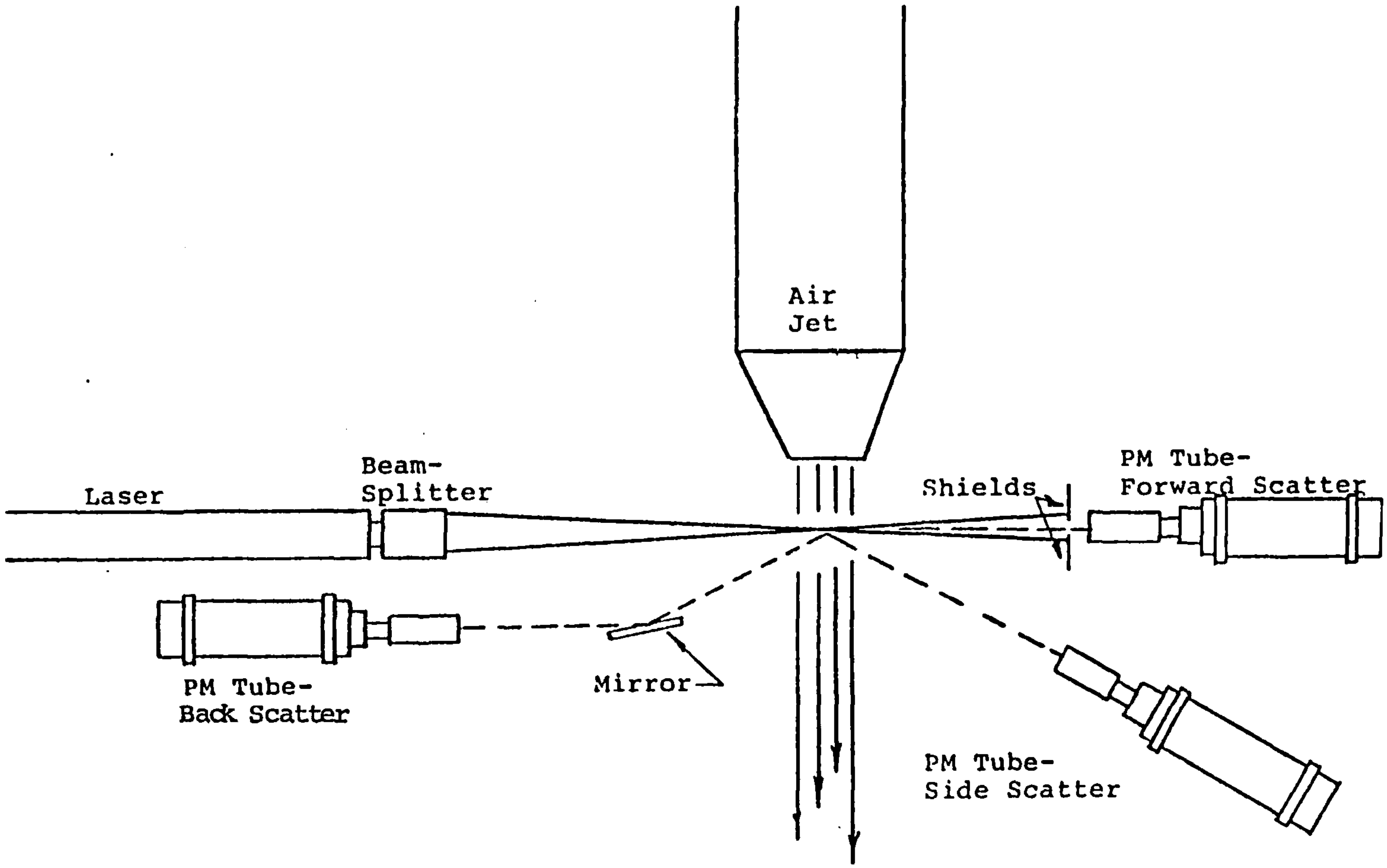


Figure 8 Scatter Angles for Laser Doppler Velocimetry

great care, and is highly responsive to local flow velocity flucuations in both magnitude and direction.

At high turbulence levels Laser Doppler Velocimetry is one of the few techniques capable of making such flow measurements (Ref 14). This is made possible by operating the Laser Doppler Velocimeter in conjunction with a frequency shifting device, such as a Phase Modulator.

There are disadvantages to the use of Laser Doppler Velocimetry as well (Ref 19). It requires that there be high quality optical access to the measurement region for both the laser beam and the photon detection unit. It must also be recognized that it is the velocities of the light scattering particles that are measured rather than the flow velocity. This introduces possible errors in turbulent regions where there may be velocity lag or slip of particles too slow in responding to the flucuating fluid flow. The scattering particles themselves often must be artificially introduced into the flow in order to provide for adequate photon scattering to make measurements practical. The signal produced by the scattering particles is a complex series of sine wave bursts of varying amplitude and modulation dependent upon where the particles pass through the control volume. This randomly changing doppler signal requires extremely sophisticated processing equipment in order to decipher the usable velocity related information.

Only with the advent of modern electronic signal processing equipment has it become possible to analyze the high frequency fluctuating signals typical of velocity measurements in turbulent fluid flow. Several methods of signal processing have been attempted, ranging from electronic spectrum analysis, frequency tracking and frequency counting to Fabry-Perot measurements for exceptionally large scale or very high frequency turbulent fluid structures (Ref 19).

Differential Doppler Laser Velocimetry (Fig 9). The most common Laser Doppler Velocimeter (Ref 5) is implemented in a straight forward design and flexible operational setup:

> Two parallel laser beams from a single laser (separated into equal intensity portions by a beamsplitter) are brought to a common focus point at the region of interest in a fluid flow field. The intersection of the twin beams at this control volume creates parallel interference fringes of light and dark dividing up the ellipsoidal intersection region. Particles passing through these light areas scatter photons which are focused by a lens arrangement onto a pinhole aperature into a Photo-Multiplier Tube. The scattered light may be collected from any direction, in forward or back-scatter mode. The Photo-Multiplier Tube outputs an electrical signal corresponding to the photons received. This signal is interpreted by the signal processing equipment to determine the fluid flow velocity.

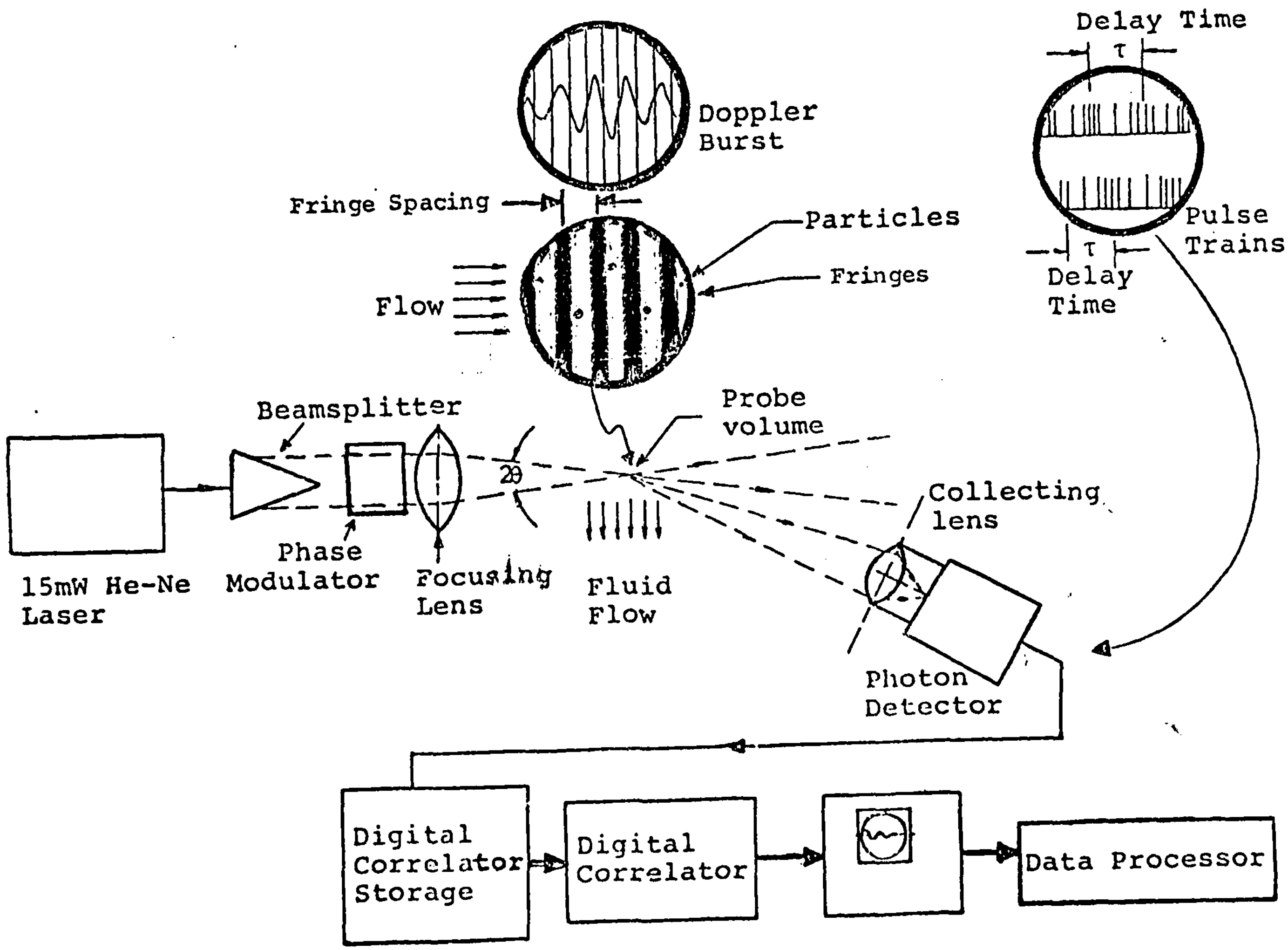


Figure 9 Operation of Laser Doppler Velocimetry

Laser interference fringes (Fig 10) are what make Laser Doppler Velocimetry possible. The fringes are formed when two coherent beams having planar wave-fronts intersect at an angle. At all locations within the intersection control volume where the wave-fronts are in phase (or out of phase by 360 degrees) there is constructive interference, reinforcing the laser beam intensity to twice its nominal value. Where the wave-fronts are out of phase there is interference decreasing the laser intensity to zero. Thus planes of light and dark fringes are formed in the ellipsoidal control volume, parallel to the bissector of the twin intersecting beams. The spacing between the fringes is proportional to the laser wavelength and inversely related to the beam intersection angle.

In most cases the intensity profile of the laser beams can be considered to be of a gaussian distribution, with the 1/(e^2) intensity level at the beam intersection denoting the boundary of the control volume, or the "effective probe size." The control volume is ellipsoidal in shape, sliced vertically by the fringes perpendicular to the direction of the fluid flow. The minor axis of the ellipsoidal control volume is a function of the diameter of the twin laser beams and varies slightly with the intersection angle of the beams. The major axis on the other hand increases rapidly as the intersection angle decreases and can introduce significant spreading of the doppler signals detected if it becomes too large.

As scattering particles move across the fringes of the control volume a flucuating light intensity is scattered and

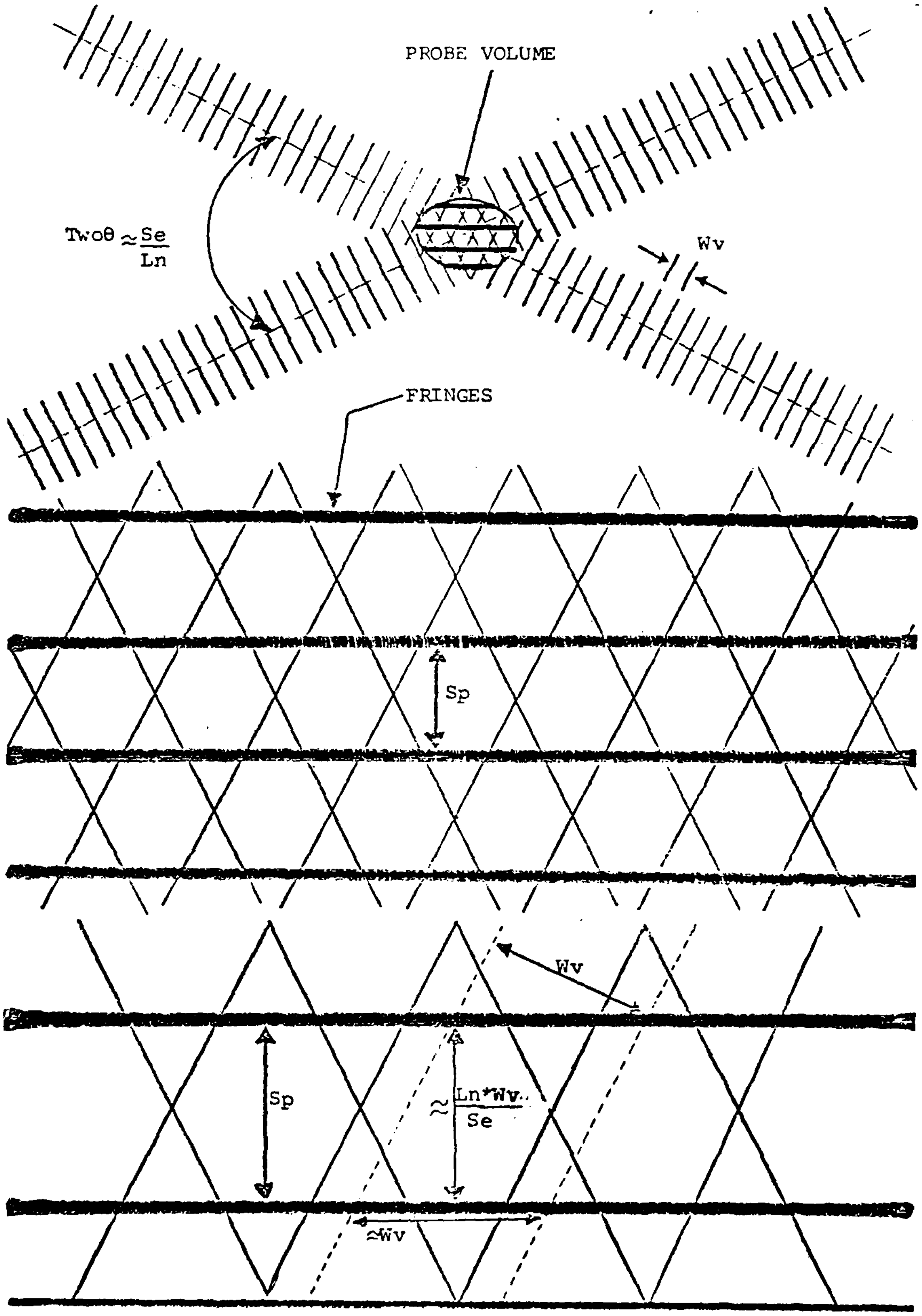


Figure 10 Interference Fringe Formation

detected by the Photo-Multiplier Tube. The Photo-Multiplier tube outputs a series of seemingly random pulses corresponding to the photons it detects. This time variant signal is processed to determine the velocity information characterizing the fluid flow.

Photon correlation (Ref 1) is the technique employed in signal processing in the time domain for the Laser Doppler Velocimetry used in this procedure. General signal processing techniques will be discussed below. Photon correlation utilizes the temporal variation of scattered light intensity arising from single scattering particles passing through the fringes of the control volume. The temporal variation of the signal is periodic in nature as many paricles follow the fluid flow. The valid information is extracted from random background noise by generating an autocorrelation function with the signal.

The autocorrelation function for random data describes the dependence of the values of the data at one time on the values of the data at a subsequent time. In this way an energy autocorrelation is obtained which persists over the signal period. Any random background noise which masks the signal will correlate to a constant value. This method of signal processing has the particular advantage over other techniques used with Laser Doppler Velocimetry in that it is more sensitive at low scattering particle densities, when scattered photons are few and seldom.

Signal Processing For Laser Doppler Velocimetry (Ref 2). The analysis of the Laser Doppler Velocimetry signal is complicated by the fact that the signal is produced as discrete bursts of energy corresponding to the scattered photons from the particles in the fluid flow. At high seeding particle densities the bursts may merge to form a nearly continuous signal, often ceasing at random intervals. The four primary methods used for processing the doppler signal are frequency tracking, burst processing, photon correlators and Fabry-Perot interferometers.

In early research using Laser Doppler Velocimetry the doppler signals were analyzed with standard frequency spectrum analyzers. These were essentially a narrow band filter constantly sweeping the suspected doppler frequency range and outputing a voltage proportional to the power present in the filter bandwidth at any instant.

In cases where the velocities are extremely high, such as boundary layer measurements in magnetohydrodynamic experiments, where the doppler frequency may be on the same order as the laser frequency, then direct spectroscopic detection of the doppler shift may be possible. In these cases Fabry-Perot interferometer-spectrometers have been employed because of their superior light gathering power and resolution.

Frequency trackers offer a means of generating an output voltage proportional to the instantaneous velocity of the fluid flow, ressembling the output from a hot-wire anemometer. It is essential to maintain a nearly continuous signal to avoid tracking drop-out with this system, and this requires very heavy seeding of the fluid with large particles (just smaller than the fringe spacing), such as polystyrene beadlets. Frequency trackers use a feedback loop to compare the incoming doppler signal with a known oscillator frequency. As the doppler frequency varies, the oscillator control voltage changes to retain a maximum output signal at a narrow band filter which has a beat frequency between the doppler signal and the oscillator. The oscillator control voltage serves as the primary measure related to the doppler frequency. Frequency trackers have difficulty coping with fluid flow having velocity flucuations of large range, and work only poorly at low seeding levels. Under such conditions a burst processor, counter or individual realization processor is preferable.

Burst processors are the only family of instruments developed specifically for Laser Doppler Velocimetry from the very beginning. Many different configurations have been designed. The principle involves first filtering an individual doppler burst signal to remove the low frequency bias. This tags the signal for zero crossover timing, which is used to determine the period of the signal. Generally two different numbers of cycles are measured, perhaps four and eight cycles, and the ratio of these is compared to a preset tolerance. This allows rejection of erroneous measurements caused by noise or poorly modulated signals. Period timing is usually accomplished by a high frequency digital clock in the range of

100 to 500 megahertz. The output of the burst processor consists of a series of voltage steps, proportional to either the doppler signal strength or frequency. The voltage corresponding to a measurement on one particle is maintained until the next signal is measured and validated, eliminating the possibility of signal drop-out. Burst processors are limited only by the bandpass filters used to reduce noise. Fluid flows with extremely large velocity fluctuations between sucessive doppler bursts can easily be studied. The burst processor is well suited for measurements in highly turbulent gas flow with low scattering particle densities.

Photon correlation (Ref 12) is the latest entry into Laser Doppler Velocimetry signal processing. The theory and application of this technique originated at the British Royal Radar Establishment in Malvern, England. Photon correlation is applicable when the scattered light level is so low that individual photon arrivals are detected. The photon density follows the intensity of particle passage through the control volume. Correlating photon arrival rate versus time over many photon bursts determines the average doppler period. Turbulence information is gleaned from the decay of the correlation function.

Photon correlators are somewhat limited by their low frequency capability and long integration times, sometimes requiring seconds or even minutes to obtain a good signal correlation. Yet it remains the only viable technique of obtaining velocity data when only a few photons are available in each doppler cycle. As mentioned earlier it is the sole technique used in this procedure.

Bias Errors In Laser Doppler Velocimetry. Several different sorts of biasing errors are potential problems in Laser Doppler Velocimetry. The probability of receiving a valid signal decreases as the particle path through the probe region varies from perpendicular to the fringes at midpoint in the control volume to some other path. A certain number of fringes must be crossed by a scattering particle in order to generate a valid doppler signal. Particle paths at large angles to the perpendicular, with the extreme case of paths parallel to the fringes, may not be detected at all. The resulting Laser Doppler Velocimeter measurement is biased to measuring a single mean velocity component perpendicular to the fringe planes in either direction.

Another bias is the unverified assumption that in a uniformly seeded unsteady or turbulent fluid flow, more of the high velocity scattering particles, rather than the low velocity ones, will pass through the control volume, biasing the velocity detected to a higher than actual velocity. Rogers (Ref 16) noted this in his measurements of flow downstream from a venturi, where the scattering particles were not in velocity equilibrium with the locally decellerated fluid, giving the measured velocity a bias to a higher than realistic value for the fluid flow, thereby supporting this bias assumption.

Additional bias errors are possible due to size variations in the seeding particles (Fig 11), and the paths they follow in their traversal of the control volume in relation to gaussian beam intensity distribution of the laser. Particles that are much less than the size of the fringes will produce a clean, well modulated doppler signal. Particles on the same order of diameter as the fringe spacing, or even larger, will produce a signal masked by noise or no doppler signal at all. Particles passing through the control volume at midpoint produce a strong, maximum strength doppler signal, but those particles passing through away from the midpath of the control volume ellipsoid will scatter a less intense laser beam and produce a smaller amplitude doppler signal.

Improper optical allignment of the Laser Doppler Velocimeter system introduces some of the largest and most serious bias errors (Ref 7). Intersection of the twin laser beams to form the control volume is critical, and improper alignment can form non-uniform fringes and varying fringe spacing. This can result in a broadening of the measured velocity distribution in the fluid flow, and can appear as high turbulence even in laminar boundary layer regions.

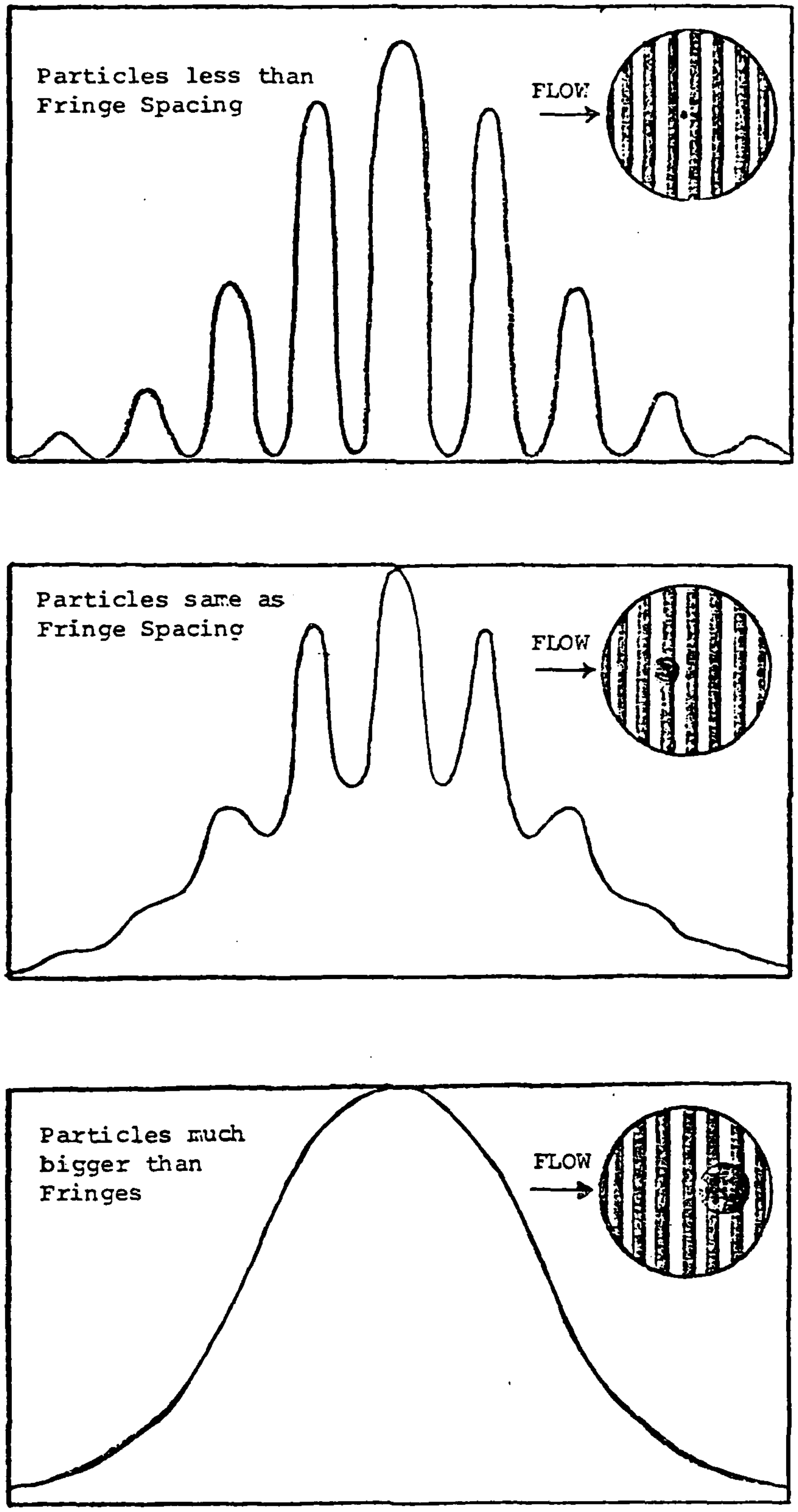


Figure 11 Effect of Scattering Particle Size on Doppler Signals

V. Hardware and Software Integration

General Considerations. Integrating the Automatic Data Acquisition System with the Laser Doppler Velocimeter required electronic interfacing of the two systems and implementation of computer software for their communication. The integration requires no permanent modifications to the Automatic Data Acquisition System, allowing its coincident utilization with other systems in other experiments. The electronic interfacing takes advantage of the built-in remote control circuitry of the Digital Correlator and its electronic data output capability. Utilizing the standard electronic interfaces of the Automatic Data Acquisition System and electronics to adapt them to the needs of the Digital Correlator, it is possible to conduct two-way communication between the devices. The communication entails the operations conducted by software controlling the Digital Correlator, transferring the data to the computer and processing of the information.

Each element involved in the integration procedure is discussed below, including the essential electronic devices, control commands and overall computer software. The Digital Correlator control and output signals establish the requirements for the interfacing techniques. The capabilities of the standard interfaces of the computer (the Hewlett-Packard 98032A and 98033A interfaces) determine the electronics necessary to interface them to the Digital Correlator. The available functions for remote control of the Digital

Correlator drive the development of the computer software and the Laser Doppler Velocimetry applications programs. The desired output information sets the goals of the overall calculations to be performed with the data.

Interfacing Electronics.

A. Digital Correlator (Ref 12). The Digital Correlator has three sockets on its rear panel, one for remote control, one for data readout and one for output to a punched card machine. The latter is not used in this procedure and is not mentioned further.

1. Remote Control. Connecting to this 25-way Amphenol 17/20250 plug allows control of the primary functions of the Digital Correlator. These functions are starting and stopping the autocorrelation, turning on and off the readout of data, stepping the data readout from one output channel to the next and clearing the data memory. When the autocorrelation is initiated by placing -5 volts on the corresponding pin of the plug, the Digital Correlator continuously analyzes the signal it is receiving from the Photo-Multiplier Tube. The Digital Correlator accumulates a digitized version of the autocorrelation curve in ninety-six storage

registers or channels, numbered four through ninety-nine. Each channel represents the autocorrelation value over that time period, where the time is the product of the channel number and the sample time switch-set on the front of the Digital Correlator. Each channel contains an eight digit decimal number of arbitrary units. These numbers are output through the readout socket in Binary Coded Decimal format when the remote control function is used.

2. Readout. The channel output of the Digital Correlator is read from a fifty pin Amphenol 17/10500 socket. The fifty data lines are used to simultaneously output the eight decimal digits of one data channel at a time in Binary Coded Decimal format. The data from one channel remains on the output lines as long as the readout remains turned on or until the readout is stepped to the next data channel.

B. Hewlett-Packard 98032A (Ref 8). This 16-bit interface is used to connect the Digital Correlator remote control with the computer. The interface has forty-two signal carrying lines for input, output, handshaking and status communication between the computer and a peripheral. Only the output lines are used in this procedure. However, because the Digital Correlator requires certain of its remote control signals to be at -5 volts, whereas the 98032A has available only +5 volt signals, an electronic translator must be connected between them to convert the signals to the proper voltages. This translator utilizes buffer and opto-isolator integrated circuits to change the logical 1, +5 volt signals of the 98032A to the logical 1, -5 volt signals needed by the Digital Correlator. This also reduces the tendancy for cross-talk and noise on the remote control inputs of the Digital Correlator, since the electrical connections between the correlation start and stop lines and the computer are eliminated.

C. Hewlett-Packard 98033A (Ref 9). This fifty line Binary Coded Decimal Interface is connected directly to the corresponding pins of the Digital Correlator readout socket. It transfers an eight digit number from the Digital Correlator to the computer.

Control Operations. Both the 98032A and the 98033A interfaces respond to commands in Hewlett-Packard Basic. Both can execute commands either from the computer keyboard or from inside a program. Both should be reset before use by the

"RESET 1" (for the 98032A) or "RESET 3" (for the 98033A).

A. Remote Control. Each remote control function for the Digital Correlator is performed by sending out a particular binary number on the 98032A. The electronic translator between the interface and the Digital Correlator converts the voltage to the required level and places it on the correct pins of the remote control plug. The command to perform this operation is "WRITE BIN 1 ; x" where the 'x' is replaced by one of the following values.

0 -- clears the interface of old values

1 -- stops the autocorrelation

2 -- turns on the readout

4 -- turns off the readout

16 -- steps the readout to next channel

32 -- clears all data from memory channels

128 -- starts the autocorrelation

Any non-conflicting combination of these numbers will perform all of the desired functions, e.g., x=32+128=160 will clear the Digital Correlator memory and start the autocorrelation. The interface should be cleared between each sucessive command (x=0) to avoid unwanted combinations.

B. Readout. When the readout is turned on by a command to the remote control, the eight digits of a particular channel appear on the readout socket output lines. These digits are read into the computer directly through the 98033A interface by executing the command "ENTER 3 ; A(I) , Status" where 'A' is the array variable that the number is to be stored in, 'I' is the index of the array, and 'Status' is a variable set by the correlator determining whether or not this is the last channel to be read. If 'Status' is found to be zero, then no more channel contents may be read until the readout is turned on again by remote control.

Software. The computer program developed in this procedure is extensive and is intended to handle most of the contingencies that might arise in operating the Laser Doppler Velocimeter in conjunction with the Automatic Data Acquisition System. Sharpe (Ref 17) clearly outlines the requirements for data processing of Laser Doppler Velocimetry information and his guidelines have been adhered to in this procedure. The program prompts the user via messages on the cathode ray tube display at all points, as to what decisions must be made, actions taken or what options are available. The program is self-starting and will load itself and begin to run any time the computer is turned on with the "AUTOST" button depressed and the cassette cartridge version of the program inserted into the T15 tape transport.

The software is functionally divided into sixteen modules. Each module performs specific tasks, from running the correlator and reading the data to fitting curves to the autocorrelation and storing the final results on disk for permanent access. The names of each module appear at the top of cathode ray tube display when the program is running, arranged according to the assigned softkey value of each. A particular module executes when its softkey is pressed.

A. Startup. When the program begins it immediately sets up the necessary data storage for computations, plotting and other tasks, as well as checking the time and thereafter keeping track of it. It asks the user for information regarding the specifics of the Laser Doppler Velocimeter setup being used in the experiment.

B. "CORREL" This module handles clearing of the Digital Correlator memory and runs the autocorrelation for ten seconds. The run time can be altered by changing the variable 'Total' in subroutine "Run_correlation" to the integer value of seconds desired.

C. "READ" The second module performs the data transfer from the Digital Correlator to the computer. It requests from a user the sample time set on the Digital Correlator and the modulator frequency set on the Phase Modulator. These are necessary in any calculations to be done with the data. The data is read from the Digital

Correlator into the array 'A' to be used throughout the entire program. The time that the data was read into the computer is recorded in order to tag particular data points. The data is quickly plotted and the graphics displayed on the cathode ray tube for five seconds. This allows a user to view the autocorrelation and determine if the data are valid and satisfactory.

D. "LOCATE" This module is used before or after running the correlator and reading the data. It is a means by which particular data points are identified to the computer. It relies upon the module "MODEL" described below. A graphical display of the airfoil in the test section of the smoke tunnel appears and the user is asked to locate the coordinates of the point at which Laser Doppler Velocimetry data is currently being taken. Locating the point is either by moving the displayed cursor with the left, right, up and down arrows, or by entering the actual coordinates of the point in millimeters measured from the lower left hand corner of the test section. The location information is used by the program to develop a velocity profile about the airfoil in the module "RESULTS." Although this section of the software is intended to describe experiments in a particular environment, it is equally applicable to any two-dimensional environment, with or without an airfoil model in place. Used as is, a different test bed can be visualized by assuming an origin at the lower left corner of the test chamber, with maximum test chamber dimensions of 1.5 meters length and 1.0 meters height. Any smaller subset of these dimensions need only ensure that when data points are located within the test chamber figure, that they fall within the actual bounds of the test environment under consideration. If a more precise description of an actual test chamber other than the "Blue Smoke Tunnel" is required, the software itself can easily be modified to handle the case.

E. "STORE" This module is part of the data base management system developed for this program. It writes all of the information pertaining to a particular Laser Doppler Velocimetry data point onto a data storage disk (over two thousand bytes) for later retrieval by other modules or use at a later date. The data storage area must be prepared first, using module "C-File" and there can only be one data storage area per flexible disk. However, each data storage area or file holds up to two hundred Laser Doppler Velocimetry data points, and usage of the data points later for module "RESULTS" is independent of how many disks are used to store data points from the same experiment.

F. "RESULTS" Probably the last module to be used in an experiment, this produces three plots on the 9872S plotter. Each plot appears the same, as a scale drawing of the test section of the smoke tunnel with the airfoil being tested in place. On two of the plots are plotted the relative magnitudes of the one-dimensional mean velocity and the turbulence intensity, respectively. The third plot nas the actual numerical values of velocity and turbulence listed at the locations of the data points. The module will plot all values for a specific angle of attack (the identifying factor), independent of how many separate flexible disks those points are stored on.

G. "Screen" and "Plotter" These short modules merely determine where the results of computations and curve-fitting will be printed, the former being the cathode ray tube graphics and the later on the 9872S plotter.

H. "Switch" Another very short module, this one allows the user to switch back and forth from the cathode ray tube graphics display to the character display.

I. "CRV-FIT" Perhaps the longest of all the modules, it is here that most of the calculations are done.

This module should be called only after a satisfactory autocorrelation has been transferred to the computer. This module locates the local maximums and minimums of the autocorrelation data. These are used to produce polynomial curve-fits and then unskew the data. From the unskewed data the mean velocity and turbulence of the fluid flow are computed. The curves are plotted and all relevent data printed on a single page for minimal hardcopy storage of the information.

Of particular interest is the polynomial curve-fitting used to unskew the data. Experimentation demonstrated that a single type of polynomial curve-fit might not be sufficient to cover the widely variant autocorrelations encountered. The skewing occurs when extraneous information, stray light, gets into the Laser Doppler Velocimetry system. By fitting a polynomial to the maximums and another to the minimums of the autocorrelation, and then finding the average of these two, an unskewing curve can be generated to remove the bias of the data. The difficulty arises in that the number of peaks (maximums) or valleys (minimums) varies from one autocorrelation to the next. In order to satisfactorily unskew all, the curve-fitting must be generic. In this module, an autocorrelation with 'N' peaks will be fit with a polynomial curve-fit of order 'N-1' using standard Least Squares techniques. The valleys are fit the same way, and the unskewing curve is the average of the two.

K. "PICKOFF" This module is for use when the autocorrelation has unavoidable noise, such as spikes, in the data. The routine provides graphical displays prompting the user to eliminate the bad data points, pick off the data to be used as the unskewing curve-fit and locate the maximums and minimums describing the mean velocity and turbulence.

L. "SEARCH" This is the heart of the data base management system for this program. It very carefully directs and leads a user through operations to purge from the flexible disk old data points that were bad or no longer needed, to reprocess old data in order to provide another look at it, to list out a common set of data points, to dump out all the information on a flexible disk (an extremely large amount of paper is thereby generated), and to summarize all of the data points on a particular disk. Each activity is independent and a user can escape at almost any point.

M. "ENTRY" This module is dedicated to past experiments. It is intended solely for entering autocorrelation data by hand from previous experiments, so that the present software can be used to process it. Once the data is entered, any of the other modules may be used.

N. "C-File" In order to have a place to store all of the voluminous information generated by this program, a file must be created on a flexible disk (or on more than one). This module creates the proper file for storage of two hundred Laser Doppler Velocimetry data points, and will check to see if an earlier file of the same type is to be destroyed. The decision is always in the hands of the user.

O. "MODEL" The program relies upon physical locations for producing displays of flow fields. This module allows the user to enter a specific airfoil shape under study into the computer memory (and onto the flexible disk), for later use in drawing the smoke tunnel test section, airfoil and flow patterns. A photograph or drawing of the airfoil of interest is placed on the 9872S plotter and using the plotter's digitizer sight the shape is traced into the computer. The user only must orient the computer as to the chord of the airfoil, and thereafter the computer can vary the angle of attack of the airfoil at the discretion of the user. This file, "MODEL:F8,1", must be present on all flexible disks used for data storage, but once made, can be copied from one flexible disk to another.

P. "Simulat" In order to acquaint the user with the software without the need for setting up and running the smoke tunnel and entire Laser Doppler Velocimeter, this module is provided. It simulates with fourier series the autocorrelation as received in previous Laser Doppler Velocimetry experiments. It is operated in place of the "CORREL" and "READ" modules. All other functions and activities are the same.

Q. "HALT" The last module stops the program, clearing memory, displays and graphics.

The overall software capability can be summarized as follows. The four primary areas of application are: operating the Digital Correlator, performing calculations with the data, storage management of the data and modelling of the airfoil under study. "CORREL" and "READ" are used to operate the Digital Correlator by running the autocorrelation function and transferring its data to the computer. Computations of turbulence intensity and velocity are done with "CRV-FIT" and "PICKOFF," and presentations of these calculations is done with "RESULTS." The large amount of information produced is stored via the "STORE" module in a data file created by "C-File," and later retrieved and re-examined via the "SEARCH" module. Data from previous experiments, recorded earlier by hand, can be entered into the computer under control of "ENTRY" and subsequently processed with the other modules. Creation of a model of the airfoil under study is done with "Model," and an individual data point is tagged with respect to the airfoil via "LOCATE." The other short modules merely provide the capability to change methods of output from screen graphics to plotter graphics, ("Screen" and "Plotter"), to switch from alpha-numeric display to graphics display on the cathode ray tube and vice versa ("Switch"), to artificially duplicate operation of the Digital Correlator for instructional purposes ("Simulat") and to stop the program ("HALT").

Operational Testing. The integrated Laser Doppler Velocimeter and Automatic Data Acquisition System was tested in progressive stages as individual elements of hardware and software were developed. The earliest tests were controlling the Laser Doppler Velocimeter remote control functions and transferring the data from it to the computer. This period coincided with Stephens' experiment (Ref 18) on a ducted ejector airfoil. The sample data presented later in this paper were taken during Stephens' experiment and subsequently processed with the software implemented in this procedure.

VI. Discussion of Laser Doppler Velocimetry Results

The desired product of this effort was to develop an integrated Laser Doppler Velocimeter system with control and computations done by an Automatic Data Acquisition System. That tangible result was achieved and exceeded. A system that can be utilized by minimally indoctrinated experimenters has been produced. It is the results that can be produced by the integrated system that are discussed below (Figs 13 through 23), providing insight into the capabiltiies now available to experimenters.

This procedure was conducted simultaneously with the experiment of Stephens (Ref 18) collecting velocity and turbulence data about a ducted ejector airfoil. The interfacing hardware of this procedure was used to effect control of the Digital Correlator and transfer data to the computer system on a limited basis under genuine experimental conditions. The data was subsequently processed with the software implemented in this procedure. Representative samples of the data collected are included here as examples of the capabilities that have been developed. The data presented are intended merely as a demonstration of the output support provided an experimenter using the software and hardware integrated in this effort. The data were acquired in conjunction with Stephens' and his independent manual effort substantiates the results presented here. However, the data herein are in no manner intended to represent a complete, overall study of the aerodynamic characteristics of the ducted ejector airfoil.

A Laser Doppler Velocimetry data point consists of an autocorrelation function output from the Digital Correlator. It is generated by measuring the scattered photons from a single location in a test environment where the twin laser beams intersect. The autocorrelation is actually a digitized curve of ninety-six numbers (eight digits or less). The autocorrelation function must be unskewed to remove bias and analyzed to determine the aerodynamic fluid velocity and turbulence intensity at that single point in the test environment. A large amount of information is required to describe and catalog a single velocity and turbulence intensity.

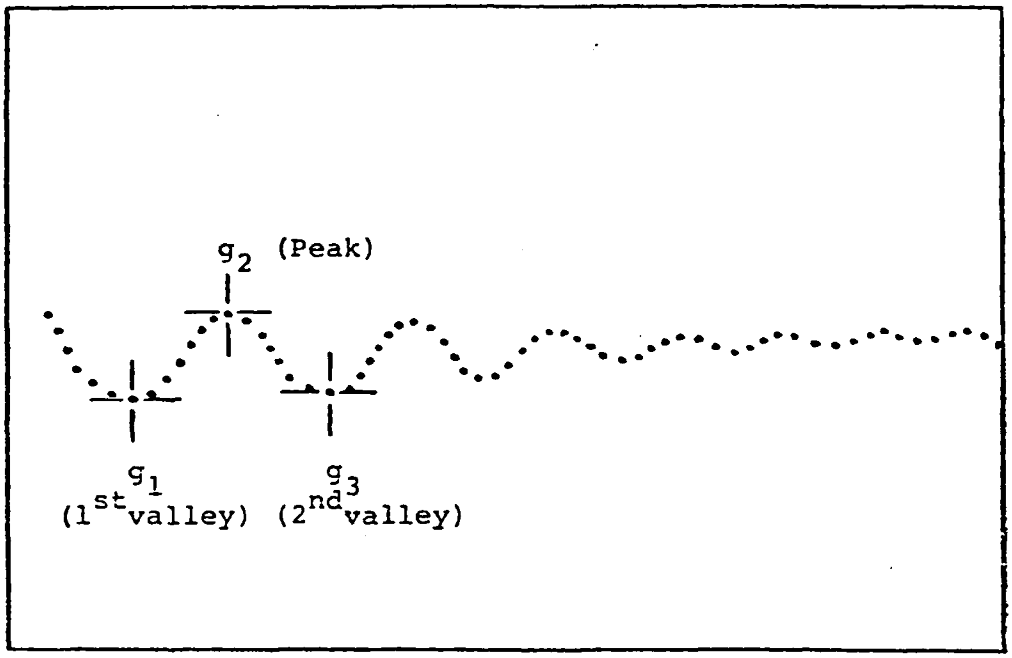
The data presented here were taken during Stephens' experiment with a ducted ejector airfoil. For these data points the ejector was not turned on, allowing only natural flow through the duct. The airfoil was at a constant fifteen degrees angle of attack. The freestream flow of the smoke tunnel was maintained at a relatively consistent speed slightly above eight meters per second and monitored continuously with a Prandtl-type pitot static tube connected to a microanemometer. Minimal scattering particle seeding density was allowed from the kerosene burners to decrease signal overloading of the sensitive Photo-Multiplier Tube from scattered photons.

Each Laser Doppler Velocimetry data point is presented as a single page of information containing all the essential characteristics. The single page format provides for efficient documentation of the experimental results. All information contained in the output is also stored permanently at the time of its creation on a flexible disk in the "Datem:F8,1" files. The data can be retrieved and reexamined at any time, and is used in creating the final result plots discussed below, showing relative velocities and turbulences.

Each data page (Figs 13 through 20) is dominated by a plot of five curves. There are also tabular listings of the relevent correlator data, experimental parameters, identifying information, a key to the plot and a drawing locating the data point in relation to the airfoil. The plot is scaled to expand the autocorrelation function so that the maximum and minimum values form the extremes of the plotting area. (This causes most correlation functions to appear to have the same slope). The original autocorrelation function read from the Digital Correlator is drawn as dashed lines. Passing through its peaks, valleys and midpoints are three dotted lines. These are the polynomial curves used to unskew the data. The unskewed autocorrelation function is drawn as a solid curve. Directly below the plot are printed the calculated turbulence intensity and velocity of the data point. Also listed are the peaks and valleys with their corresponding original autocorrelation numbers from the Digital Correlator. Other information is included describing the laser parameters, the date and time the data point was taken (not when the plot was produced), the actual coordinates of the data point, the angle of attack of the experiment (used to rotate the airfoil model), the frequency of the phase modulator and an identifying label. The values important to calculations are G1, G2, G3, Pk2, R. The first three are the autocorrelation values of the unskewed curve (Fig 12) at the first valley (G1), the immediately following peak (G2), and the second valley (G3). Pk2 is the channel number of the peak corresponding to G2. R shows the decay of the autocorrelation function and is the ratio (G2-G1)/(G2-G3). The complete method for computing velocity and turbulence intensity is detailed in Appendix A.

Eight data points are presented here (Figs 13 through 20), including two in the freestream flow of the smoke tunnel, three above the ducted ejector airfoil, one in the narrow throat of the ejector duct and two below the airfoil. The velocities of these data points range from 86% of the freestream velocity, below the midspan of the airfoil, to 151% of the freestream velocity above the leading edge of the airfoil, to a maximum of 157% of the freestream velocity at the narrow throat of the ejector duct. The turbulences range from non-turbulent (0% in the freestream) to highly turbulent (25% above the trailing edge of the airfoil).

Figures 13 and 14 are the non-turbulent freestream measurements. Figures 15, 16 and 17 are above the airfoil, with the highest measured turbulence located above the trailing edge of the airfoil (Fig 17). The latter case was the only one



Location of important numerical values

View on oscilloscope

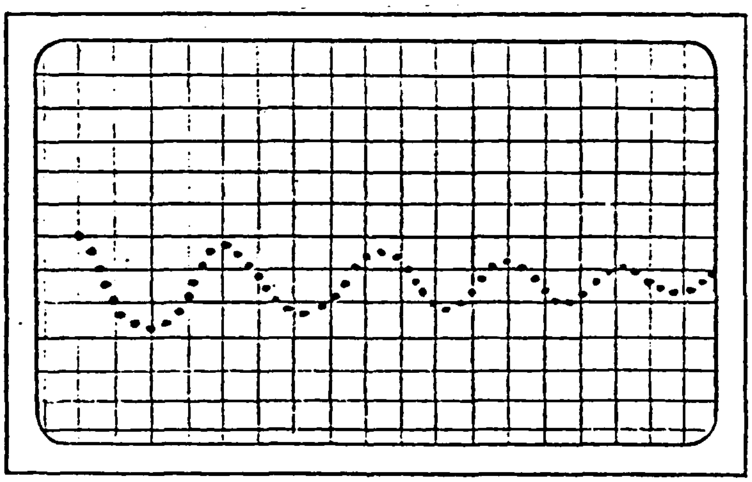
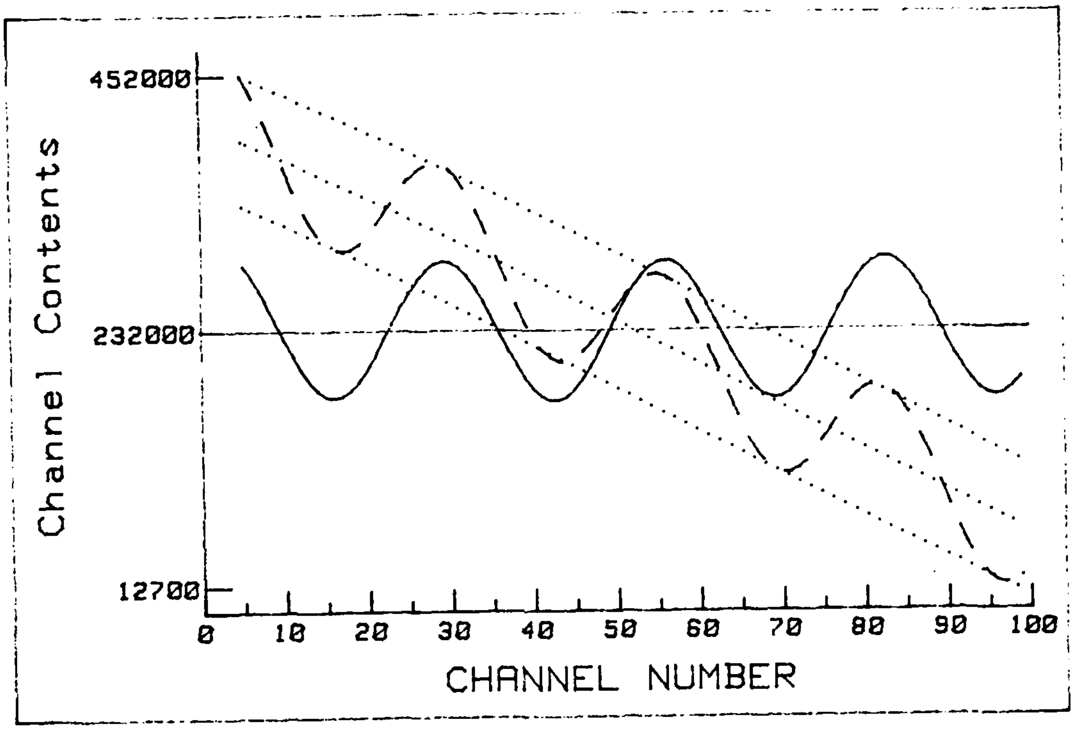


Figure 12 Location of G1, G2, and G3 on Autocorrelation Function

requiring use of the Phase Modulator to clarify the autocorrelation function. Figure 19 is the measurement in the contraction region of the ejector duct. Figures 18 and 20 are below the airfoil.

The final results are an attempt to visualize an approximation of the overall fluid flow about an airfoil. Figures 21, 22 and 23 are scale drawings of the airfoil in the smoke tunnel flow visualization region, at the selected angle of attack. These three figures show the contributions from each of the eight separate data points. Plotted on Fig 21 is the relative horizontal velocity component measured by the Laser Doppler Velocimeter for each respective data point. The relative turbulence intensities at the data points are plotted in Fig 22. A numerical catalog of the velocity and turbulence at each data point is shown in Fig 23. These plots are produced at user discretion or at completion of a particular experiment, via the results option of the software developed in this procedure. They provide a general view of the flow field.



Turbulence Intensity: 0%   VELOCITY= 8.4 meters/sec

Unskewed data	——
Curvefitting	....
Original data	----

<u>CORRELATION DATA</u>

5	451545	Peak
17	300116	Valley
28	375829	Peak
44	204491	Valley
55	280019	Peak
70	108711	Valley
81	183898	Peak
97	12729	Valley
99	18741	Peak

Identifier:
FREESTREAM

Modulator:
0 Hz

Sample Time: .150us
Wavelength: 6328A
Beam Radius:.55mm
Half Fringe:32um
17 fringes

G1= 174095
G2= 291352
G3= 171450
Pk2= 28
R= .97794

DATE: 03/23
TIME: 14:07

Coordinates:
X= 190 mm
Y= 470 mm

Angle of attack:
15 degrees

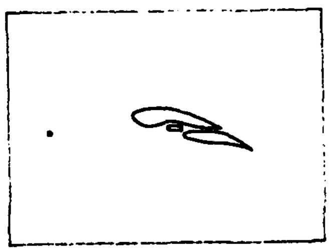
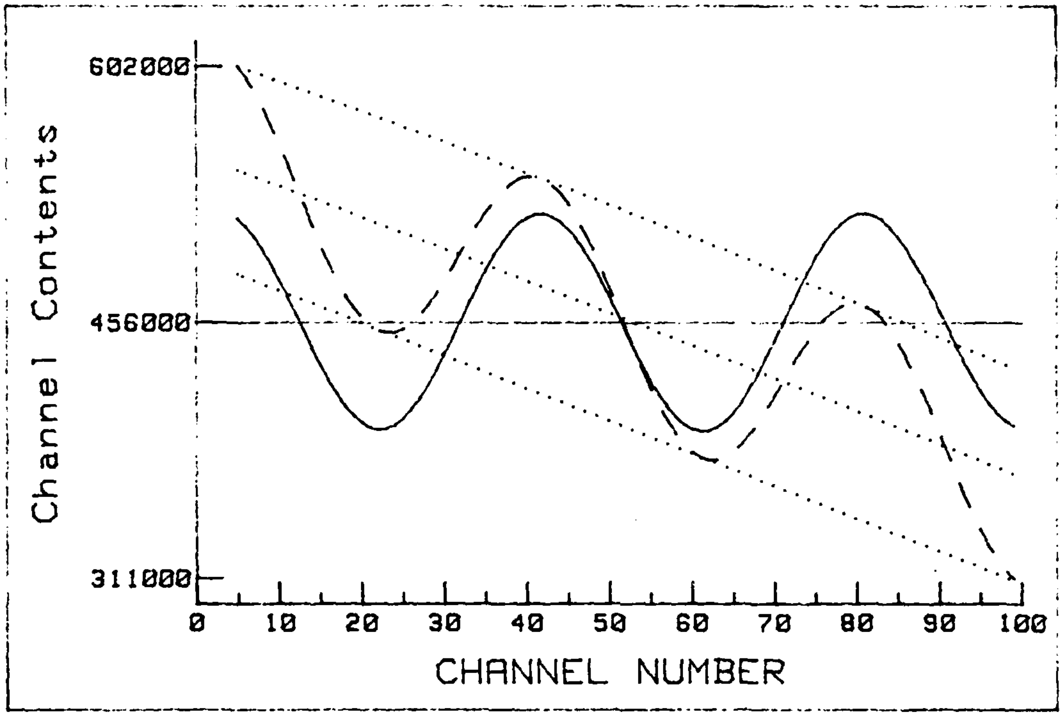


Figure 13 Freestream Flow



Turbulence Intensity: 0%   VELOCITY= 8.3 meters/sec

CORRELATION DATA

5	601730	Peak
23	450548	Valley
41	539440	Peak
62	378365	Valley
80	467260	Peak
99	311185	Valley

Identifier:
FREESTREAM

Modulator:
0 Hz

Sample Time: .100us
Wavelength: 6328A
Beam Radius:.55mm
Half Fringe:32um
17 fringes

G1= 395674
G2= 517868
G3= 394689
Pk2= 41
R= .99200

DATE: 03/23
TIME: 15:37

Coordinates:
X= 190 mm
Y= 610 mm

Angle of attack:
15 degrees

Unskewed data ——
Curvefitting ····
Original data ----

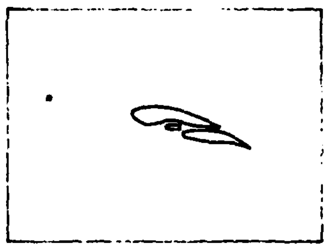
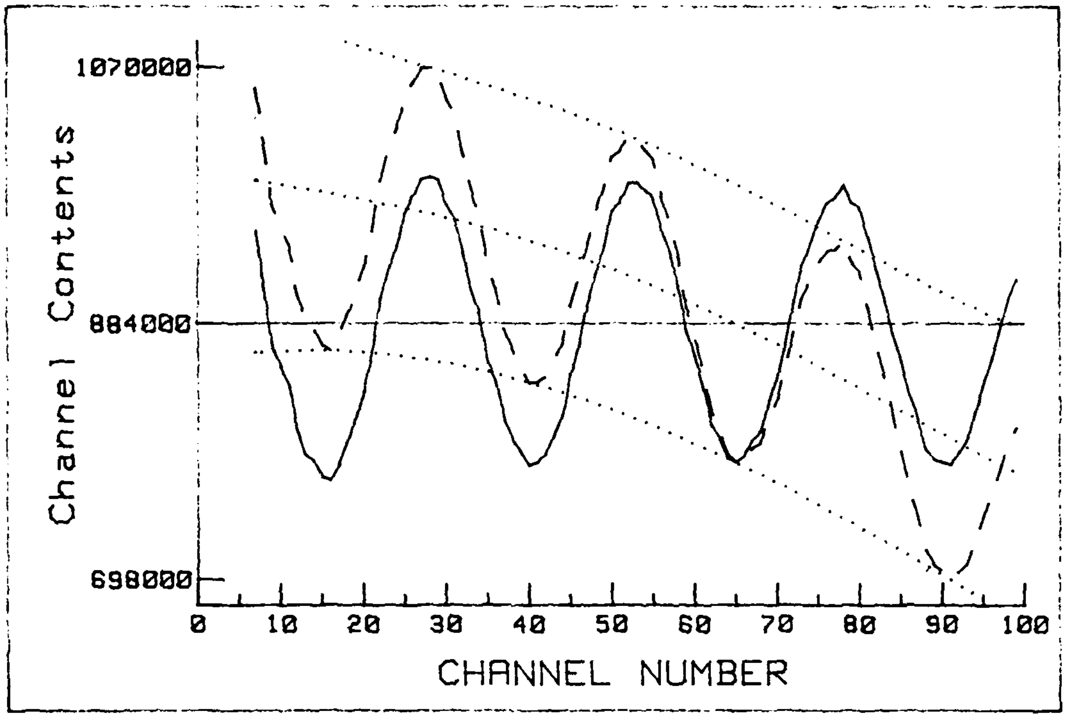


Figure 14 Freestream Flow



Turbulence Intensity: 5%   VELOCITY= 12.7 meters/sec

CORRELATION DATA

7	1054709	Peak
16	864553	Valley
28	1069801	Peak
40	841369	Valley
52	1020475	Peak
65	783322	Valley
78	944384	Peak
91	698261	Valley
99	807850	Peak

Identifier:
LEADING EDGE

Modulator:
0 Hz

Sample Time: .100us
Wavelength: 6328A
Beam Radius:.55mm
Half Fringe:32um
17 fringes

G1= 770196
G2= 990137
G3= 781082
Pk2= 28
R=1.05207

DATE: 03/26
TIME: 17:34

Coordinates:
X= 587 mm
Y= 611 mm

Angle of attack:
15 degrees

Unskewed data ——
Curvefitting ····
Original data ----

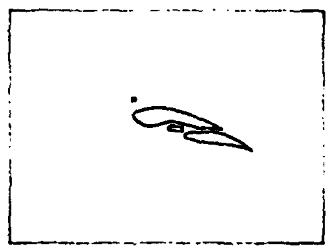
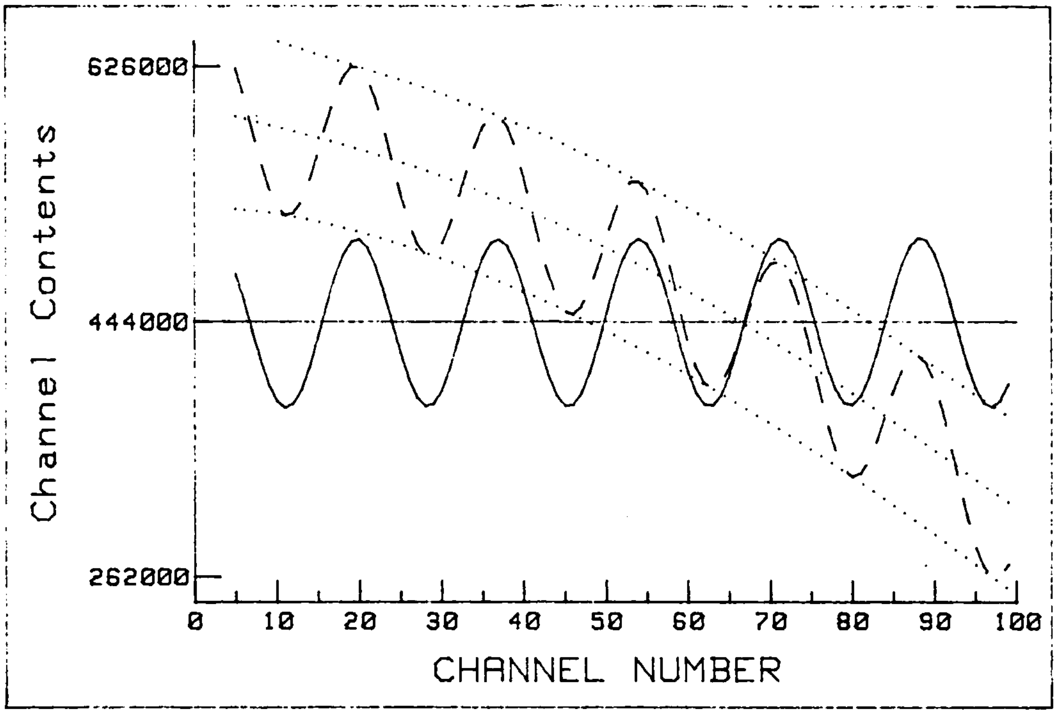


Figure 15 Flow Above Leading Edge



Turbulence Intensity: 2%   VELOCITY= 12.4 meters/sec

CORRELATION DATA		
5	624529	Peak
11	519872	Valley
20	625668	Peak
29	491185	Valley
37	590874	Peak
46	449143	Valley
54	544249	Peak
63	396108	Valley
71	486820	Peak
80	333234	Valley
88	419845	Peak
97	261894	Valley
99	270363	Peak

Identifier:
ABOVE MIDSPAN

Modulator:
0 Hz

Sample Time: .150us
Wavelength: 6328A
Beam Radius:.55mm
Half Fringe:32um
17 fringes

G1= 382536
G2= 502619
G3= 383452
Pk2= 20
R=1.00768

DATE: 04/30
TIME: 19:47

Coordinates:
X= 890 mm
Y= 600 mm

Angle of attack:
15 degrees

Unskewed data	——
Curvefitting	....
Original data	----

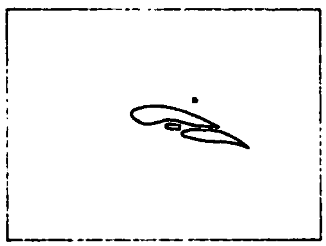
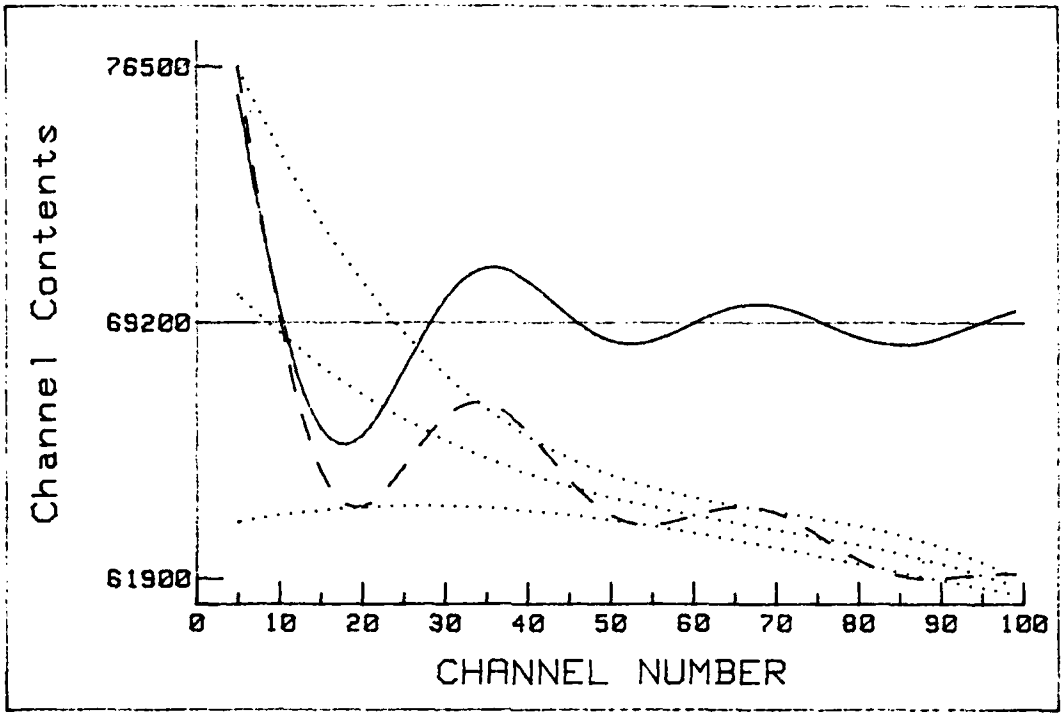


Figure 16 Flow Above Midspan



Turbulence Intensity:25%   VELOCITY= 9.2 meters/sec

CORRELATION DATA

5	76460	Peak
19	63956	Valley
34	66940	Peak
54	63464	Valley
66	63979	Peak
89	61937	Valley
98	62075	Peak
99	62066	Valley

Identifier:
ABOVE TRAILING

Modulator:
-63500 Hz

Sample Time: .100us
Wavelength: 6328A
Beam Radius:.55mm
Half Fringe:32um
17 fringes

G1= 65748
G2= 70771
G3= 68607
Pk2= 34
R=2.32083

DATE: 06/04
TIME: 20:18

Coordinates:
X=1100 mm
Y= 520 mm

Angle of attack:
15 degrees

Unskewed data	——
Curvefitting	....
Original data	----

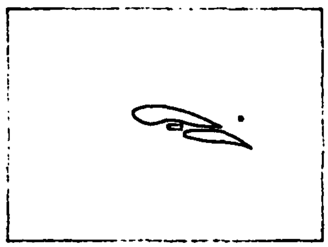
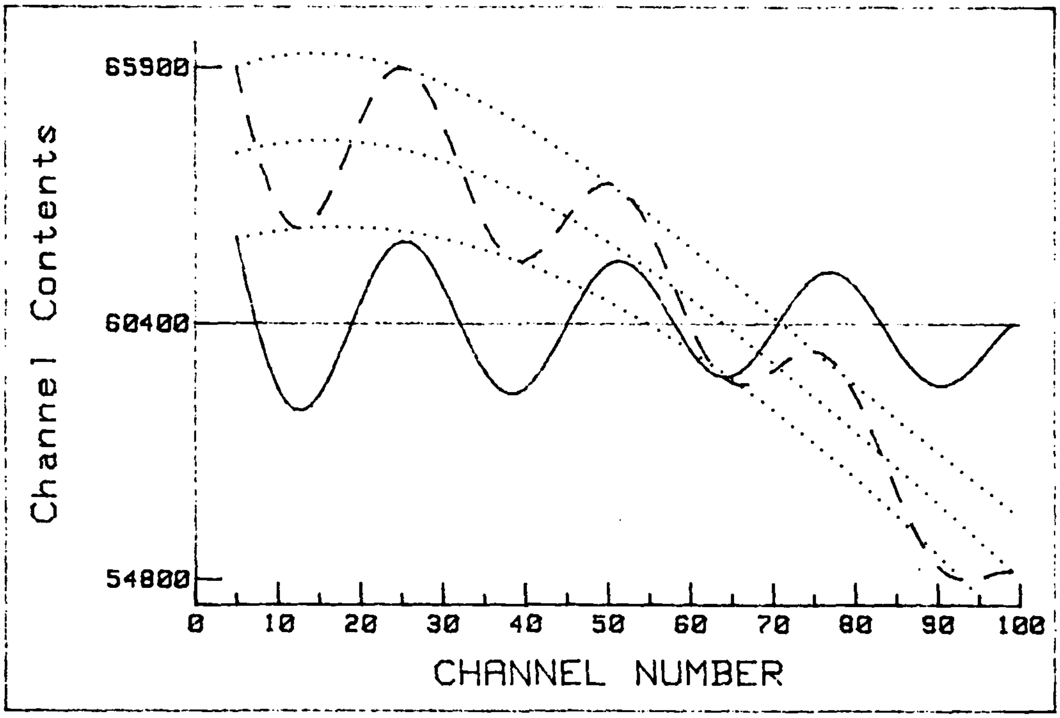


Figure 17 Flow in Wake Above Trailing Edge



Turbulence Intensity: 8%   VELOCITY= 7.2 meters/sec

CORRELATION DATA

5	65908	Peak
13	62411	Valley
25	65902	Peak
39	61715	Valley
50	63392	Peak
66	59028	Valley
75	59769	Peak
93	54806	Valley
99	54994	Peak

Identifier:
BENEATH

Modulator:
0 Hz

Sample Time: .200us
Wavelength: 6328A
Beam Radius:.55mm
Half Fringe:32um
17 fringes

G1= 58461
G2= 62134
G3= 58842
Pk2= 25
R=1.11576

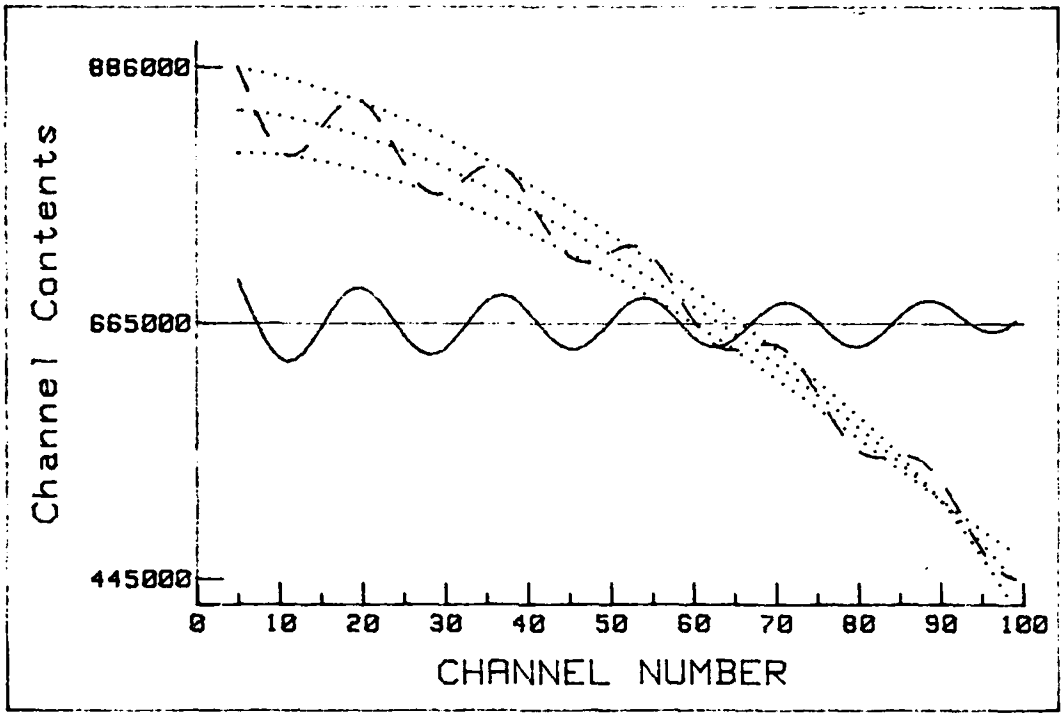
DATE: 04/24
TIME: 21:15

Coordinates:
X= 700 mm
Y= 450 mm

Angle of attack:
15 degrees

Unskewed data ——
Curvefitting ····
Original data ----

Figure 18 Flow Beneath Ductway Entrance



Turbulence Intensity: 7% VELOCITY= 13.2 *meters/sec*

CORRELATION DATA		
5	886420	Peak
11	810023	Valley
19	858855	Peak
29	776232	Valley
36	802632	Peak
47	718561	Valley
52	732468	Peak
65	642189	Valley
69	648250	Peak
83	549529	Valley
85	550906	Peak
99	444532	Valley

Identifier:
MID DUCT

Modulator:
0 Hz

Sample Time: .150us
Wavelength: 6328A
Beam Radius:.55mm
Half Fringe:32um
17 fringes

G1= 632248
G2= 695630
G3= 638194
Pk2= 19
R=1.10354

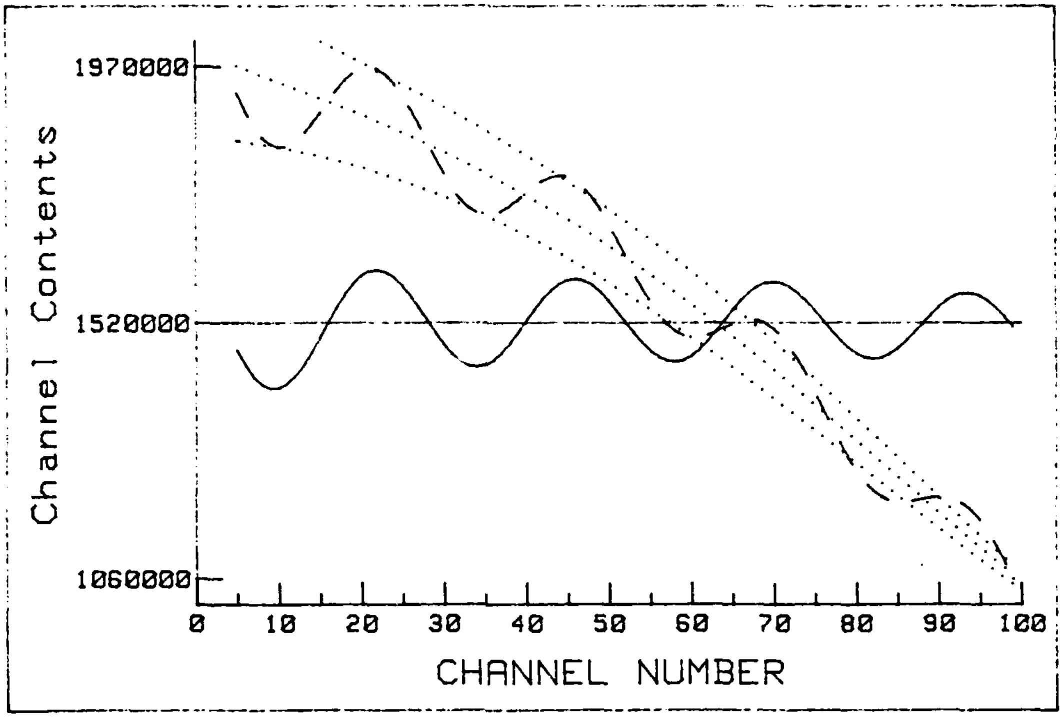
DATE: 05/18
TIME: 10:09

Coordinates:
X= 918 mm
Y= 491 mm

Angle of attack:
15 degrees

Unskewed data	——
Curvefitting	....
Original data	----

Figure 19 Flow in Ductway Throat



Turbulence Intensity:11%   VELOCITY= 8.8 meters/sec

CORRELATION DATA

5	1926775	Peak
10	1830771	Valley
21	1974484	Peak
35	1711001	Valley
44	1781209	Peak
60	1492315	Valley
67	1523803	Peak
86	1198580	Valley
90	1207948	Peak
99	1061366	Valley

Identifier:
TRAILING EDGE

Modulator:
0 Hz

Sample Time: .200us
Wavelength: 6328A
Beam Radius:.55mm
Half Fringe:32um
17 fringes

G1= 1401067
G2= 1612208
G3= 1439158
Pk2= 21
R=1.22011

DATE: 06/15
TIME: 16:14

Coordinates:
X=1088 mm
Y= 388 mm

Angle of attack:
15 degrees

Unskewed data	——
Curvefitting	....
Original data	----

Figure 20 Flow Below Trailing Edge

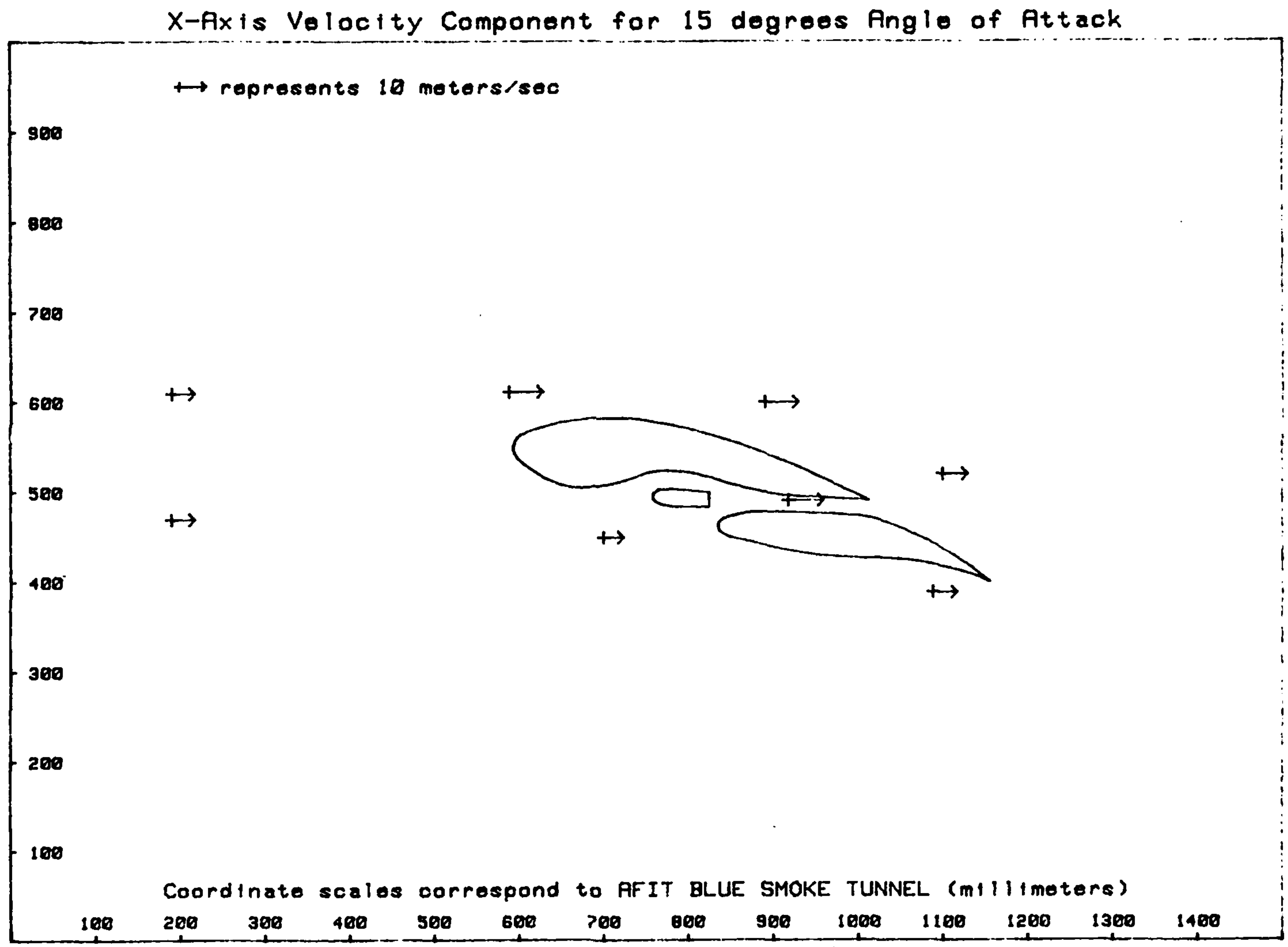


Figure 21 Overall Flow Visualization -- 1 Dimensional Velocity Component

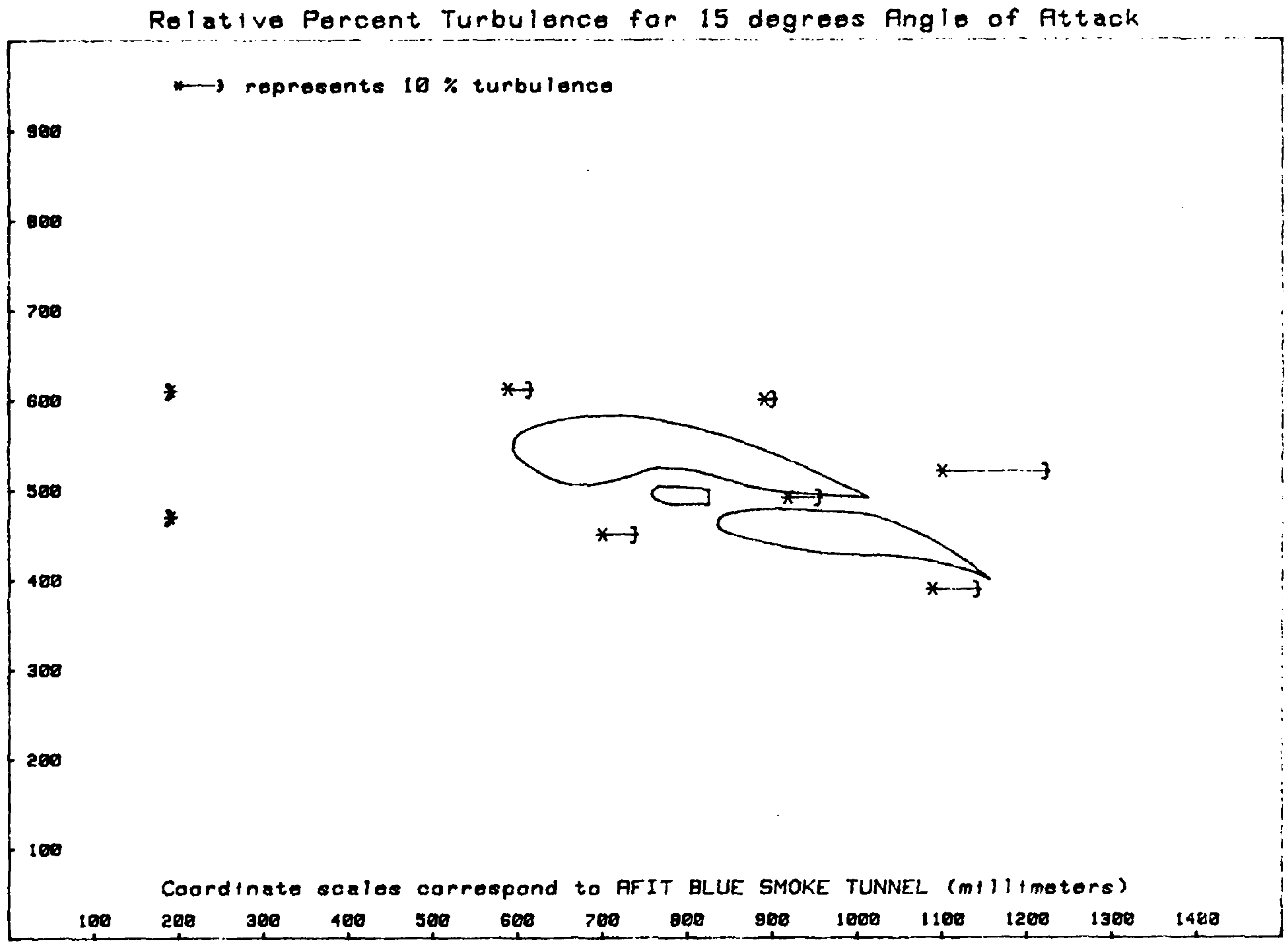


Figure 22 Overall Flow Visualization — Relative Turbulence Intensity

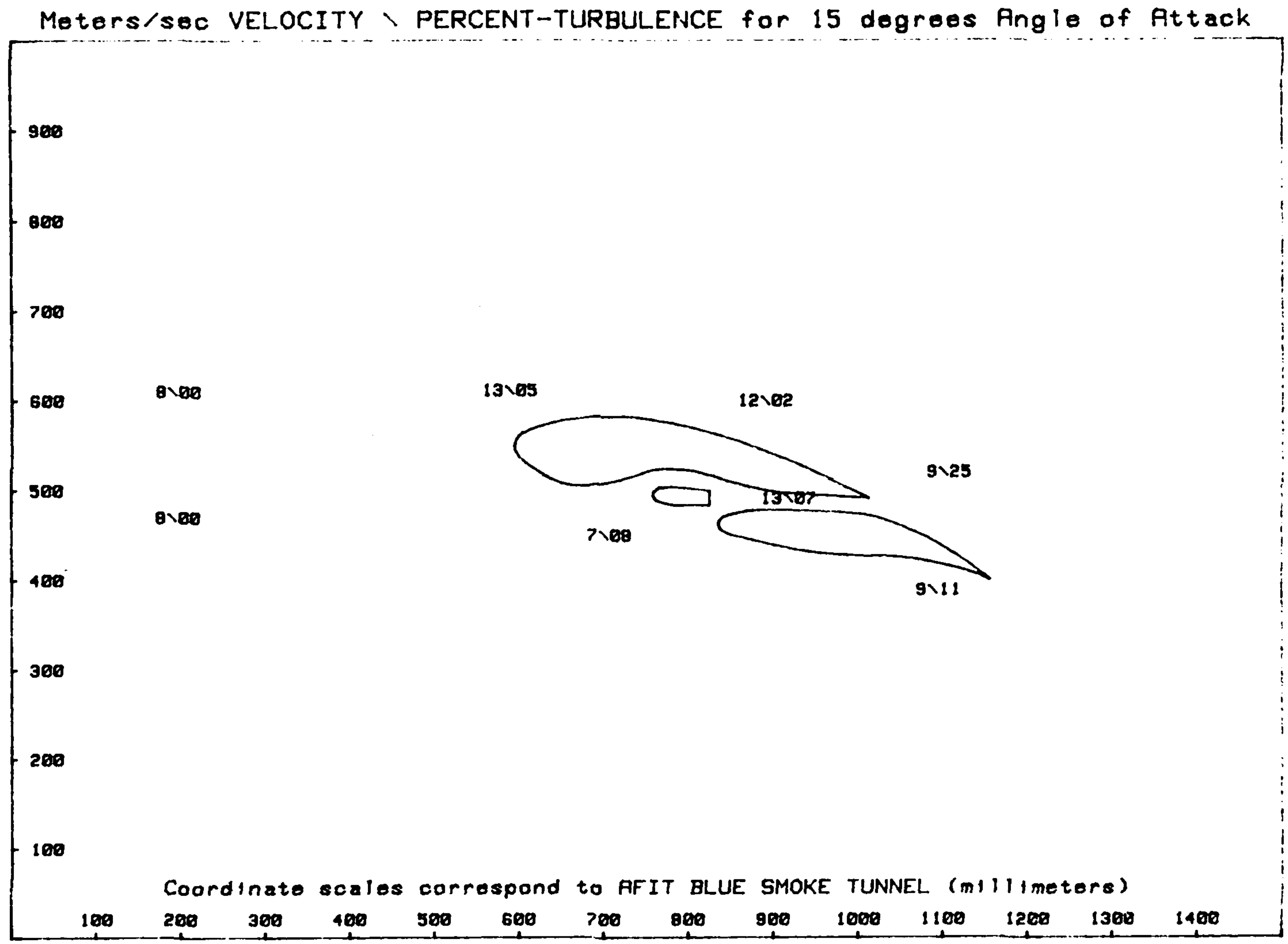


Figure 23 Overall Flow Visualization -- Numerical Results

VII. Summary and Conclusions

Summary. The Automatic Data Acquisition System has been sucessfully integrated with the Laser Doppler Velocimeter to increase the Air Force Institute of Technology experimental capabilty for aerodynamic fluid flow studies. Hardware interfaces were designed and tested as an integral part of this research, to control the Digital Correlator and to transfer its data to the Automatic Data Acquisition System computer. Software was implemented to control the interface electronics, conduct data transfer and perform the necessary calculations to compute fluid flow turbulence intensity and velocity. Computer output was formatted to provide complete documentation of Laser Doppler Velocimetry experimentation. A data base management system was developed to store and retrieve Laser Doppler Velocimetry data for permanent referral and ease of operation.

The integration of the Automatic Data Acquisition System with the Laser Doppler Velocimeter improves the ability of experimenters to collect and process extensive data in real time for fluid flow experiments. It eliminates the need for tedious and lengthy manual data recording and entry into remote computers for calculations. It provides immediate feedback as to equipment performance, test conditions and experimental results. Completion of this procedure has produced a system that will enable experimenters to devote their time and energy [illegible] evaluation of experimental results rather than to the [illegible]ary to obtain results.

The goals and objectives of this procedure were met with a high degree of success. A working, integrated Automatic Data Acquisition System and Laser Doppler Velocimeter was developed for operation by any minimally indoctrinated experimenter. The system duplicates classical results and manual computations.

Conclusions. Completion of this research has lead to the following conclusions.

A. Depending on the type of curve-fit used to unskew the autocorrelation functions, variances in the computed turbulence intensities can be found. These variances are generally no more than a few percent. The greatest discrepancies are in the unskewing of relatively non-turbulent autocorrleation functions. In some cases non-turbulent flow can appear as slightly turbulent (1 to 2%). Rogers (Ref 16) also noted such a tendancy. Turbulences below two percent may be regarded as essentially non-turbulent flow conditions. In the realm of 2 to 30% turbulence intensity the results are deemed as credible.

B. In most cases of the data taken and used herein from Stephens' experiment (Ref 18), the autocorrelation functions were skewed, due to the nature of the background noise in the laboratory (stray light). Often the display on the oscilloscope appeared as unskewed, but when the data were transferred to the computer and scaled, the slight skewing became evident. The curves had to be unskewed prior to computation of the turbulence intensity or else non-turbulent flow may have been indicated.

C. Optical alignment of the twin laser beams to form the laser probe control volume and focusing the Photo-Multiplier Tube on that control volume were the most critical aspects of conducting the Laser Doppler Velocimetry experiment. Improper alignment caused a poor, distorted or even unusable autocorrelation function. Proper alignment produced a clean, damped or undamped sinosoidal curve. (Skewing of the curve is from stray background light). The process of aligning the optics for each separate data point remained the most time consuming and exacting effort required in the Laser Doppler Velocimetry experiment.

D. Utilization of standard, removable interfaces in connecting the Automatic Data Acquisition System to the Laser Doppler Velocimeter made possible the use of the computer in a broad range of experiments without permanent modifications, thus avoiding exclusive dedication of the computer to the Laser Doppler Velocimeter.

VIII. Recommendations

The completion of the integration of the Automatic Data Acqusition System with the Laser Doppler Velocimeter has opened up opportunities for utilizing the Laser Doppler Velocimeter to investigate and catalog turbulent fluid flow phenomena previously deemed tedious and unproductive. As further research it is recommended:

A. Further verification and validation of the turbulence computation techniques employed in the software developed in this procedure should be performed through measurement of classical turbulent fluid flow conditions.

1. The fully integrated system should be used to measure the turbulence behind a grid and compared with results from more classical methods, such as hot-wire anemometry. Conduct of a classical experiment with well defined turbulence levels will provide further validation of the methods used in this procedure for curve-fitting, unskewing and turbulence calculation. The experiment should be conducted in the Air Force Institute of Technology 9x9 inch white wind tunnel, Building 640, Laboratory 142, Air Force Institute of Technology School of Engineering. Robinson's data (Ref 15), with grid of known

porosity, should be reproduced. Optical windows for this tunnel are available for optical access to the test chamber by the Laser Doppler Velocimeter. Robinson's computer controlled hot-film anemometer can be used to take the same data for comparison.

2. A second classical turbulence comparison test can be made for a high velocity free jet. Kirchner's data (Ref 10) for hot-wire and hot-film anemometry in a high subsonic plane free jet should be duplicated, using the facilities at the location mentioned above.

B. An even more advanced and capable system can be developed if the hardware and software from Robinson (Ref 15) and Kirchner (Ref 10) are integrated with the hardware and software developed in this procedure. The final system should be capable of handling Laser Doppler Velocimetry, hot-wire and hot-film anemometry simultaneously in any test environment. The system would then be self-validating and automatic.

C. The Laser Doppler Velocimeter capabilty should be improved by introducing a two-dimensional velocity measurement system (requires two pair of twin laser beams perpendicular to each other). Either an additional Digital Correlator would be necessary or a different signal processing system could be used. Lasers of two different frequencies or polarized diferently would also be necessary. The system would provide a more realistic description of fluid flow conditons in two dimensions.

D. Additional further studies should concentrate on evaluating various bias errors of the Laser Doppler Velocimeter system. Examinations should be made of accuracy requirements in laser optical alignment, laser beam departure from true gaussian profile beam power intensity, beam convergence and diameter decrease when focussed by a lense, effects of scattering particle density and size flucuations and background light noise. The effects of each should be characterized to determine their influence on Laser Doppler Velocimetry credibility.

E. A final experiment is to examine the turbulence introduced in a test environment by physical probes, such as hot-wire, hot-film or pitot static anemometry systems. The Laser Doppler Velocimeter can be used to map the turbulence formed by low speed incompressible fluid flow around physical probes and analyze the impact on the turbulent flow that the probes are designed to measure.

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APPENDIX A

VELOCITY AND TURBULENCE COMPUTATIONS FOR LASER DOPPLER VELOCIMETRY

In order to facilitate referral to the software developed under this procedure, the variable names, labels and mathematical conventions used in the software will be presented here, rather than switching to the more conventional and traditional Greek alphabet. Variables may be one or more alphanumeric characters, with only the first letter capitalized. Numerical operations are symbolized by:

+ -- addition

- -- subtraction

* -- multiplication

/ -- division

^ -- exponent (e.g., A^B is A raised to the power B)

SIN -- trigonometric sine

ATN -- trigonometric inverse tangent

The variables in the software used in calculating velocity and turbulence are in alphabetical order:

Fd -- unshifted doppler frequency of photon signal

Fdp -- doppler frequency of photon signal

Frequency -- oscillator frequency of the phase modulator, positive for drive mode, negative for inverted

G1 -- autocorrelation value at the first valley of the autocorrelation curve

G2 -- autocorrelation value at the peak immediately following the first valley (G1)

G3 -- autocorrelation value of the second valley

Ln -- focal length of the focusing lens

Nn -- number of interference fringes in the control volume at the intersection of the laser beams

PI -- numeric value of pi (3.14...)

Pk2 -- Digital Correlator channel number corresponding to the peak represented by G2

R -- decay ratio of the autocorrelation curve

Ro -- radius of laser beam control volume, assumed the same as the laser beam radius (@ 0.00055 meters)

Se -- separation of laser beams at the focusing lens

Sp -- interference fringe spacing (fringe half width)

St -- Digital Correlator sample time

Ti -- computed turbulence intensity

Two0 -- the included angle between the laser beams at their point of intersection

U -- computed velocity

Ud -- uncorrected velocity indicated by doppler signal

Wv -- wavelength of the laser used (6.328 E-06 meters)

The first step in the calculation is to determine the included angle between the laser beams at their point of intersection (Fig 24):

Two0 = 2 * ATN [Se / (2 * Ln)]

$$Two\theta \approx \frac{Se}{Ln} \qquad Sp = \frac{Ln * Wv}{Se}$$

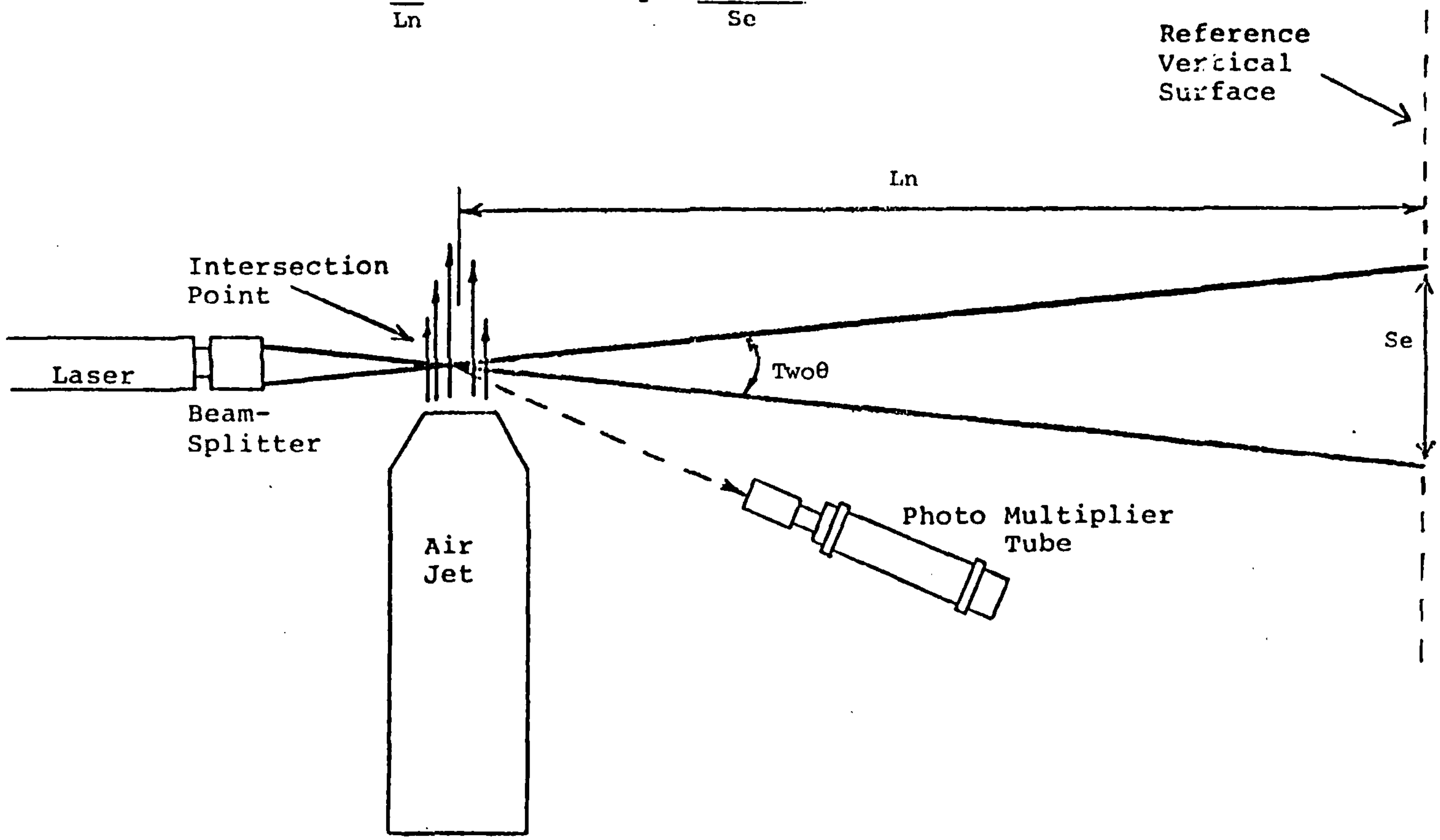

Figure 24 Calculation of Angles and Fringe Spacing

The next step is to find the fringe spacing as in Fig 25 (assuming an index of refraction for air alone at 1.0):

Sp = (Ln * Wv) / Se

The total number of fringes visible in the control volume is given by:

Nn = Ro / Sp

The velocity indicated by the doppler signal and uncorrected for frequency shifting by the phase modulator is:

Ud = Se / [(Pk2 - 3) * St]

where 3 is subtracted from the channel number because the first information channel starts at 4 on the Digital Correlator. The doppler frequency associated with this velocity is:

Fdp = 2 * Ud * [SIN (Two0)] / Wv

By adding or subtracting the phase modulator oscillator frequency as appropriate (positive for drive, negative for inverted mode) the unshifted doppler frequency of the fluid velocity is simply:

Fd = Fdp + Frequency

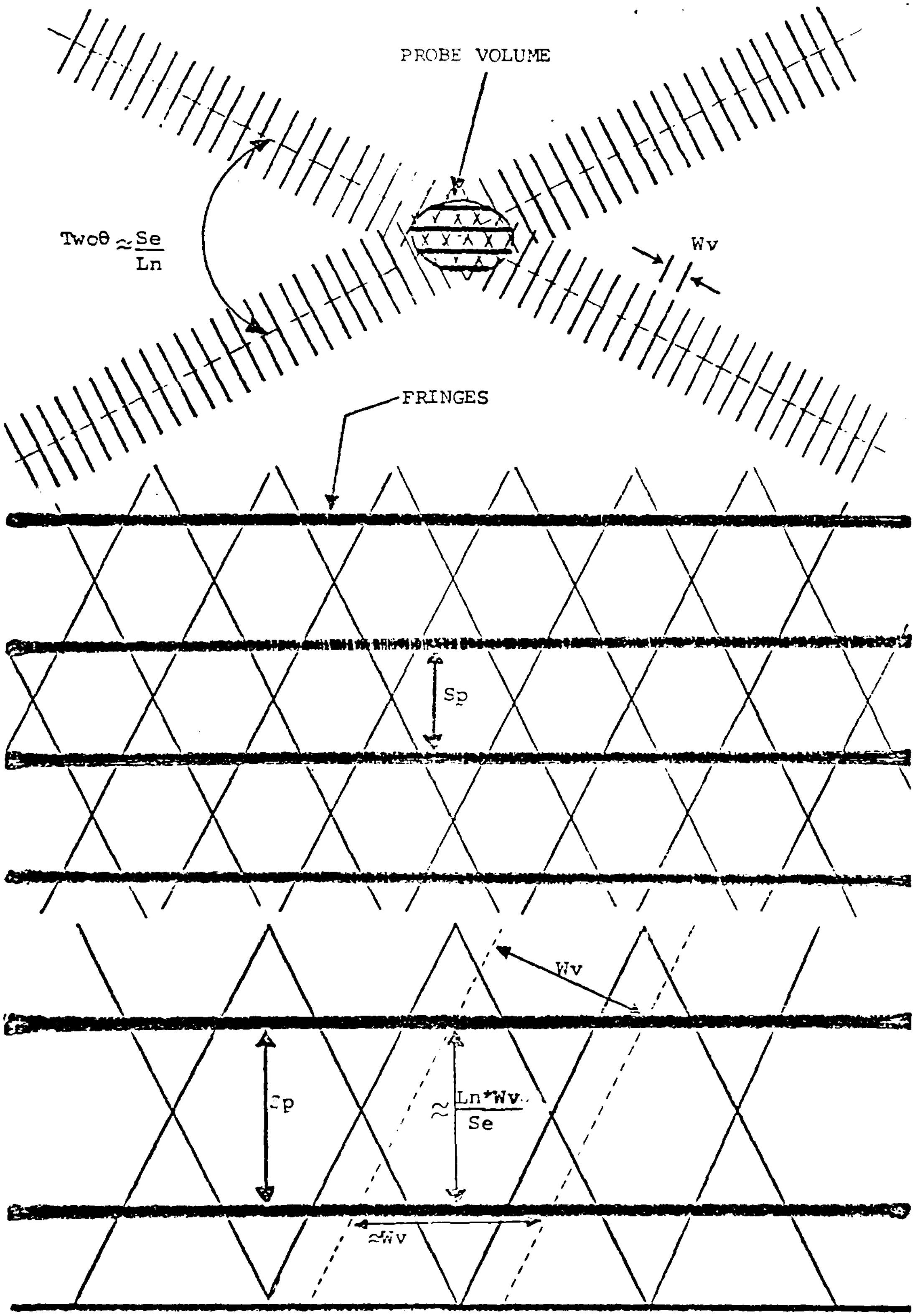

Figure 25 Formation of Interference Fringes

Inverting the previous calculation of velocity to frequency, the actual velocity of the flow based on the unshifted doppler frequency is:

$$U = Fd * Wv / [2 * SIN (TwoO)]$$

The calculation of the turbulence intensity is dependent of the decay rate of the autocorrelation function (Fig 26), given by:

$$R = (G2 - G1) / (G2 - G3)$$

and then the turbulence intensity fraction is:

$$Ti = 1/PI * [0.5*(R-1)*U/Ud + 0.5/(Nn\hat{}2)] \hat{} 0.5$$

For cases where the phase modulator is not used, and thus Frequency = 0 these equations reduce to the same equations as are used in other manual computations of velocity and turbulence intensity (refs 16 and 18).

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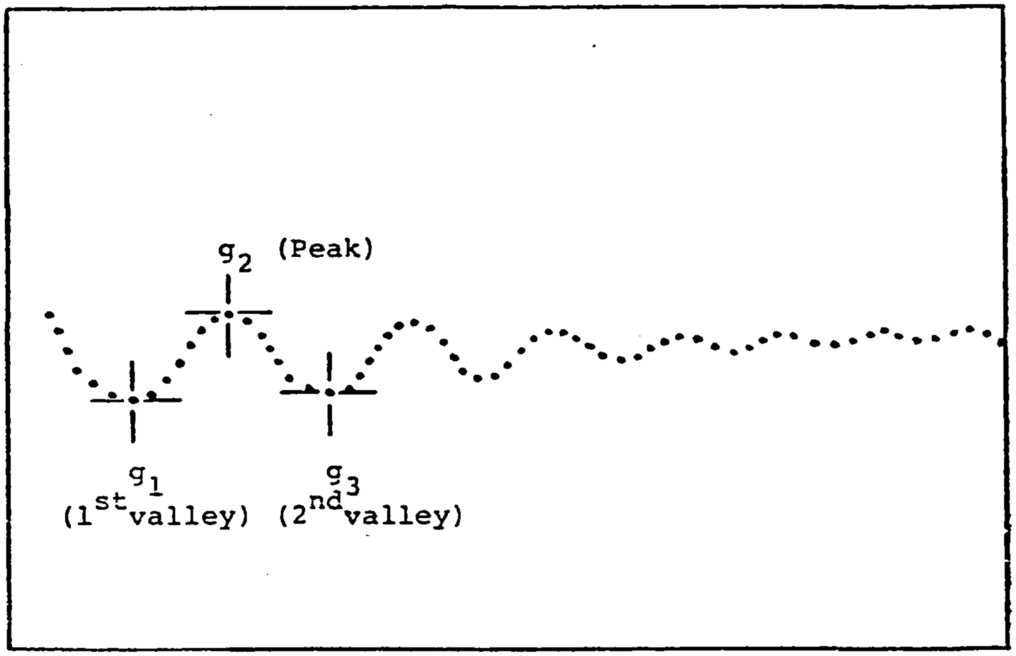


Location of important numerical values

View on oscilloscope

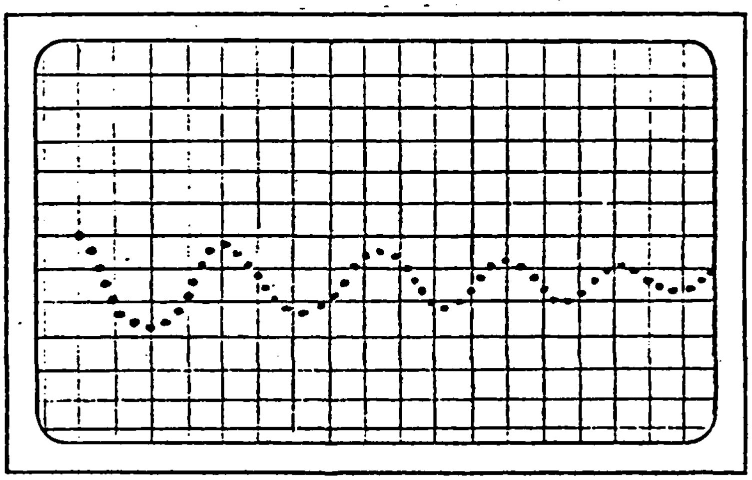


Figure 26 Location of G1, G2, and G3

APPENDIX B

LASER DOPPLER VELOCIMETER SET-UP AND OPERATION

References 12,16 and 20 contain excellent starting points for acquaintance with the Laser Doppler Velocimeter. This guide is intended to supplement those sources in regards to facets of set-up and operation peculiar to this procedure.

The Laser Doppler Velocimeter used herein was previously mounted (Ref 20) on a large, stable optical bench specifically designed for operation in conjunction with the AFIT Blue Smoke Tunnel.

1. Laser. The helium-neon laser is attached to the optical bench via two aluminum mounting points, using four screws. On the front of the laser tube is connected the beamsplitter. The co-axial cable from the laser is connected to the laser power supply unit, which in turn is plugged into a standard 110 volt source. The laser is turned on at the switch on the power supply unit. This assembly is shown in Fig 27.
2. Phase Modulator. The Phase Modulator (Figs 28 and 29) is fastened down on a track in front of the laser, aligned with the twin beams emerging from the beamsplitter. The two co-axial cables from its base are connected to the Output 1 and Output 2 plugs on the front of the Phase Modulator Drive

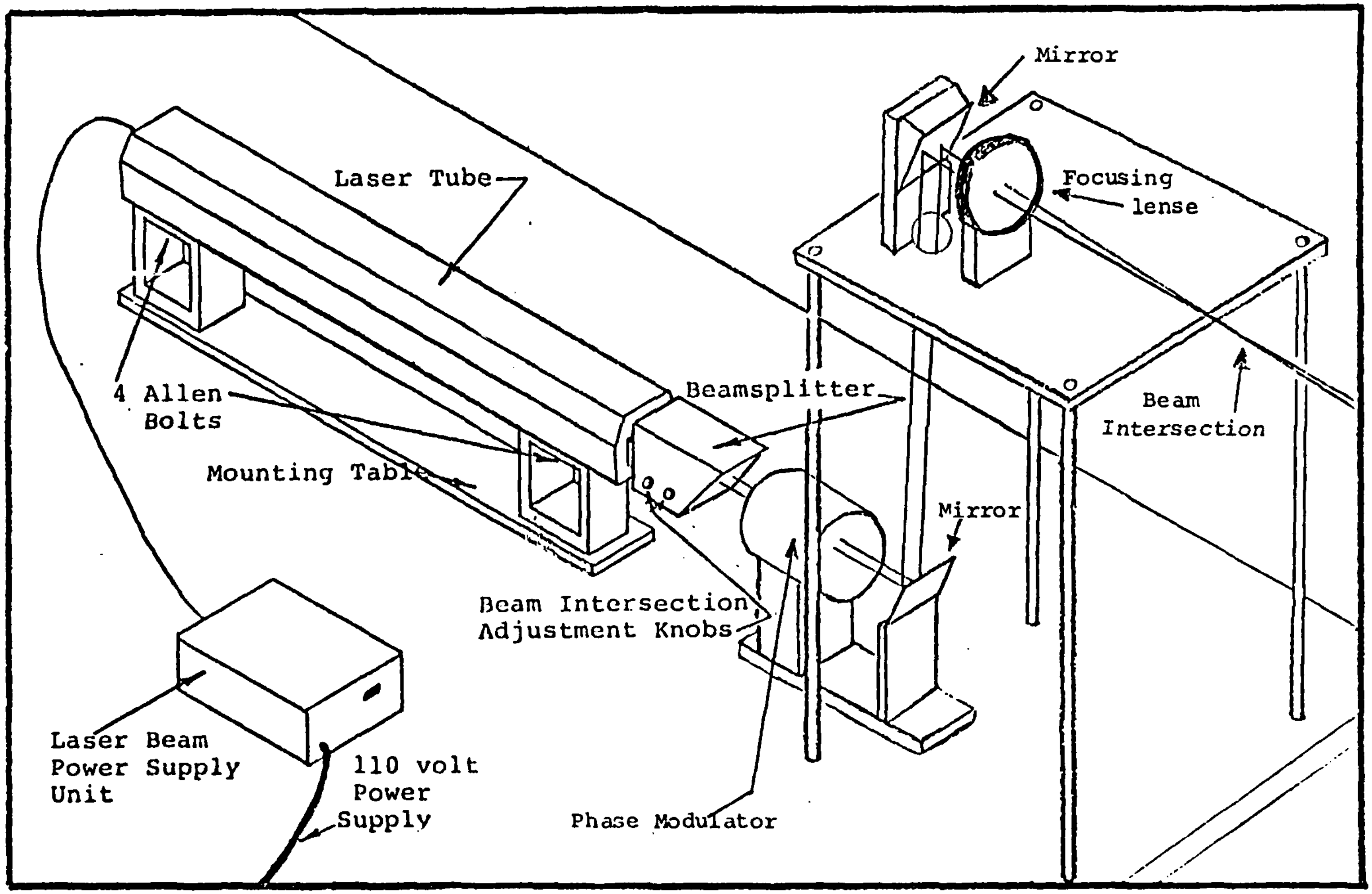


Figure 27 Physical Layout of Laser Doppler Velocimeter

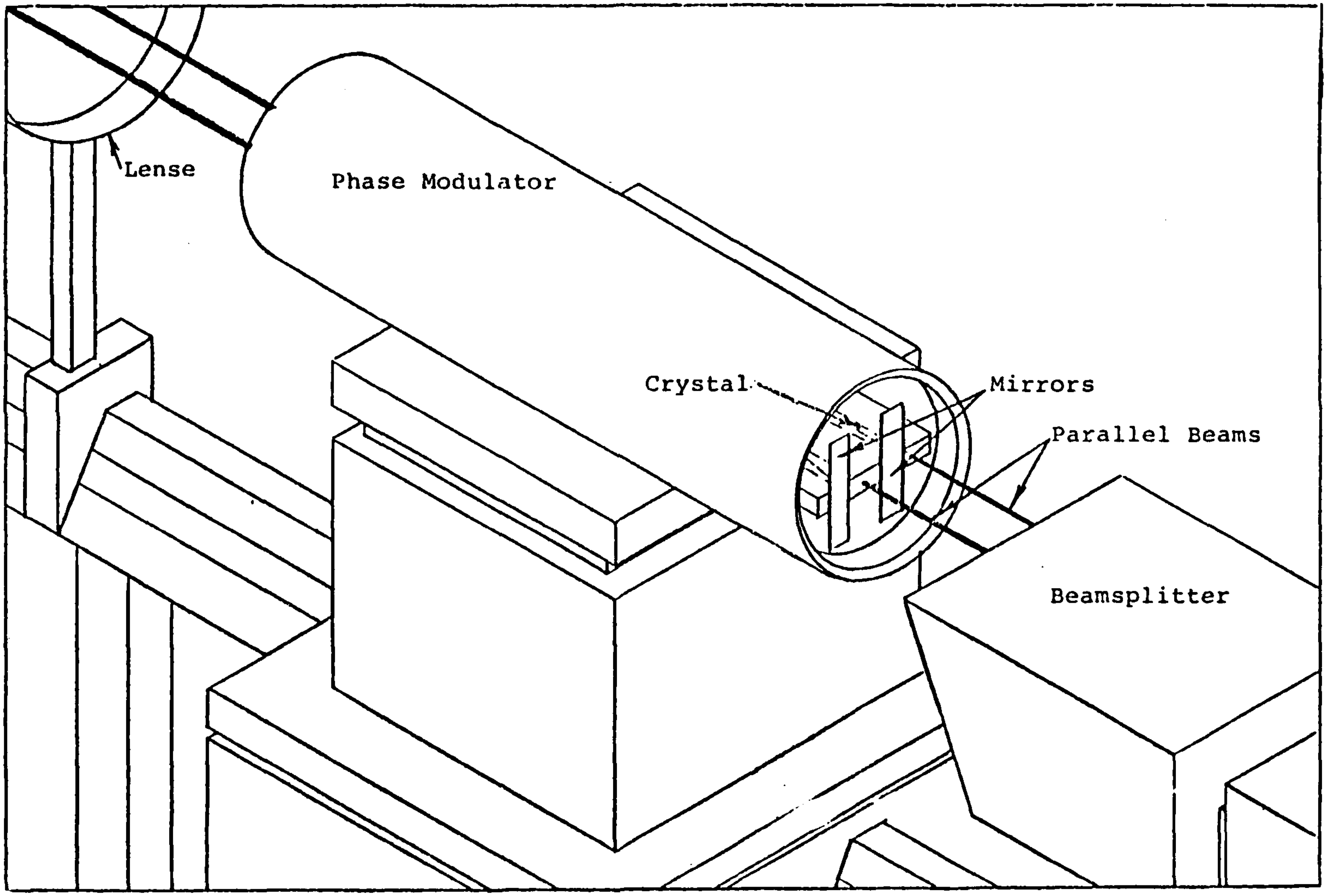


Figure 28 Alignment of Laser Beams with Phase Modulator

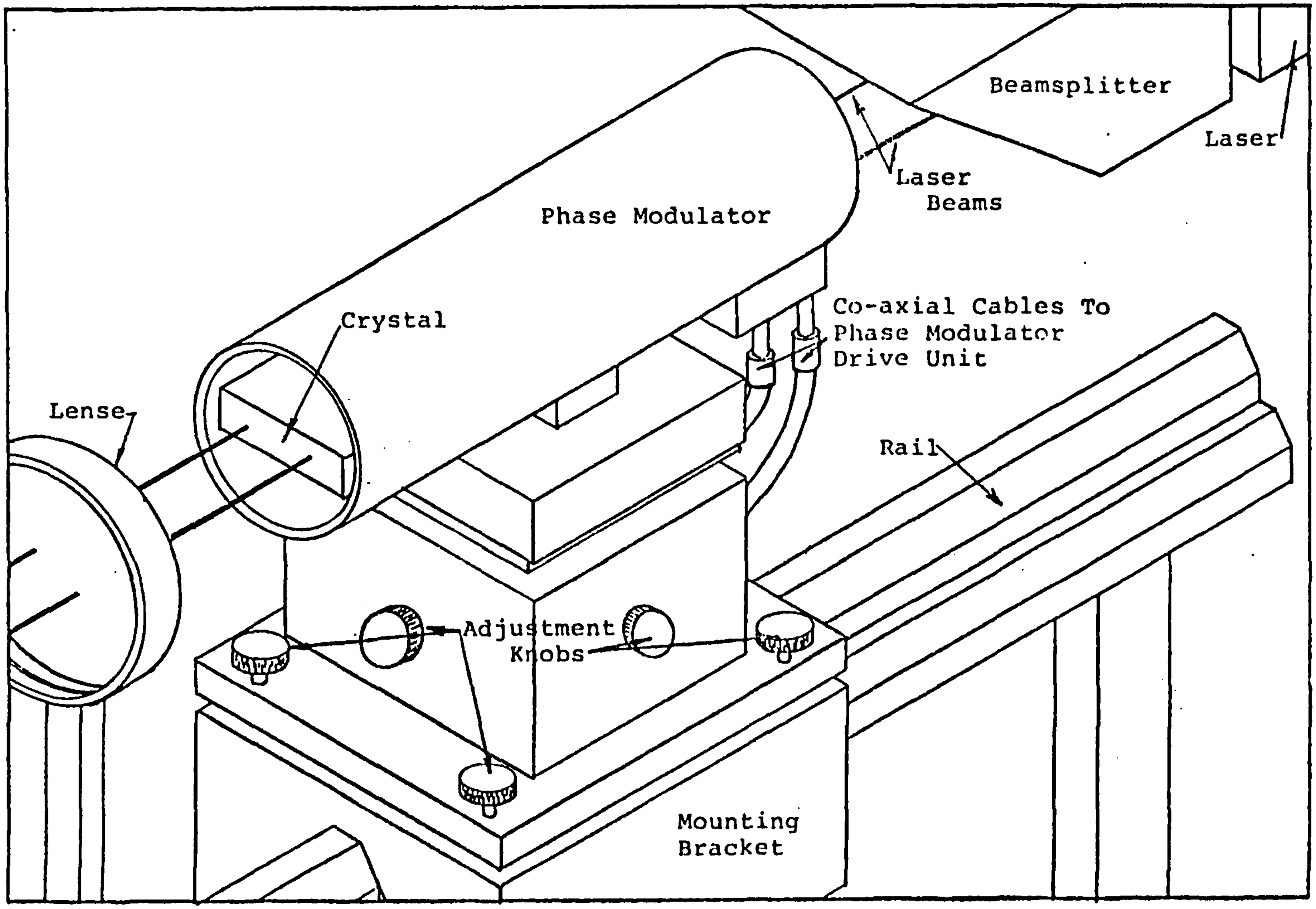


Figure 29 Setup of Phase Modulator in Optical Path

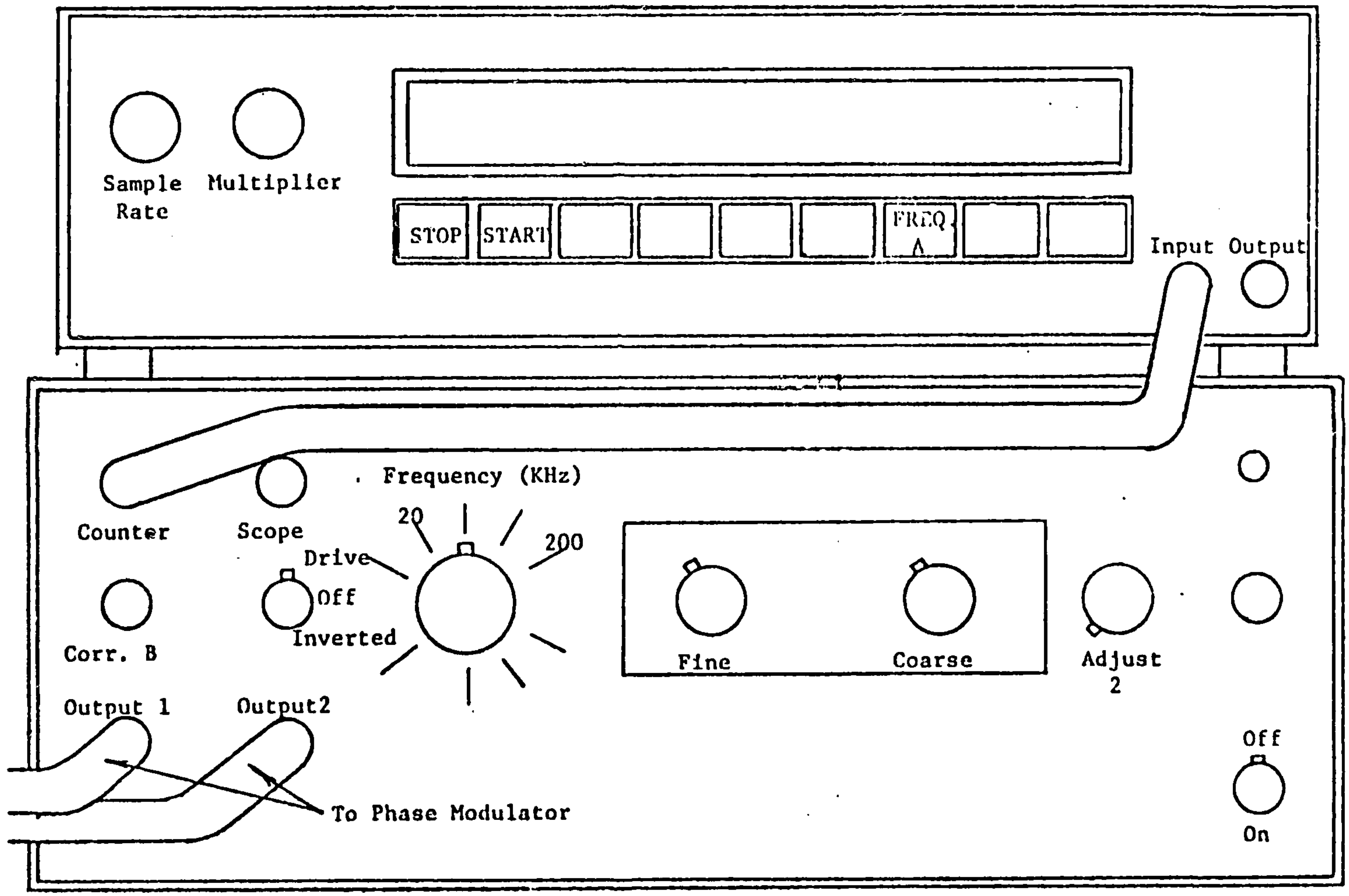


Figure 30 Phase Modulator Driver and Frequency Counter

unit (Fig 30). The counter output from the drive unit is connected to a frequency counter input.

3. Optics. The optical bench is designed so that the probe control volume (defined by the intersection of the laser beams) can be moved in two dimensions, perpendicular to the test chamber (towards and away from the test chamber) and vertically along the test chamber. This control is allowed by sending the parallel laser beams through a periscope prior to being focused to an intersection point.

4. Photo-Multiplier Tube (Figs 31 and 32). The Photo-Multiplier Tube is attached via a triangular support and adjustment rail on top of the optical periscope arrangement. It is ofset at an angle of several degrees to the direction of the laser beams, in a backscatter mode.

5. Digital Correlation Equipment (Figs 33 and 34). The equipment is best situated with the storage unit on the bottom, then the Digital Correlator and the oscilloscope on top. The equipment is located to provide ample working room for an experimenter, with easy access to the controls.

6. Safety Precautions. Extremely high voltages are used in this equipment and many of the pieces are fragile and expensive. Careful operation will avoid accidental injuries to body or equipment.

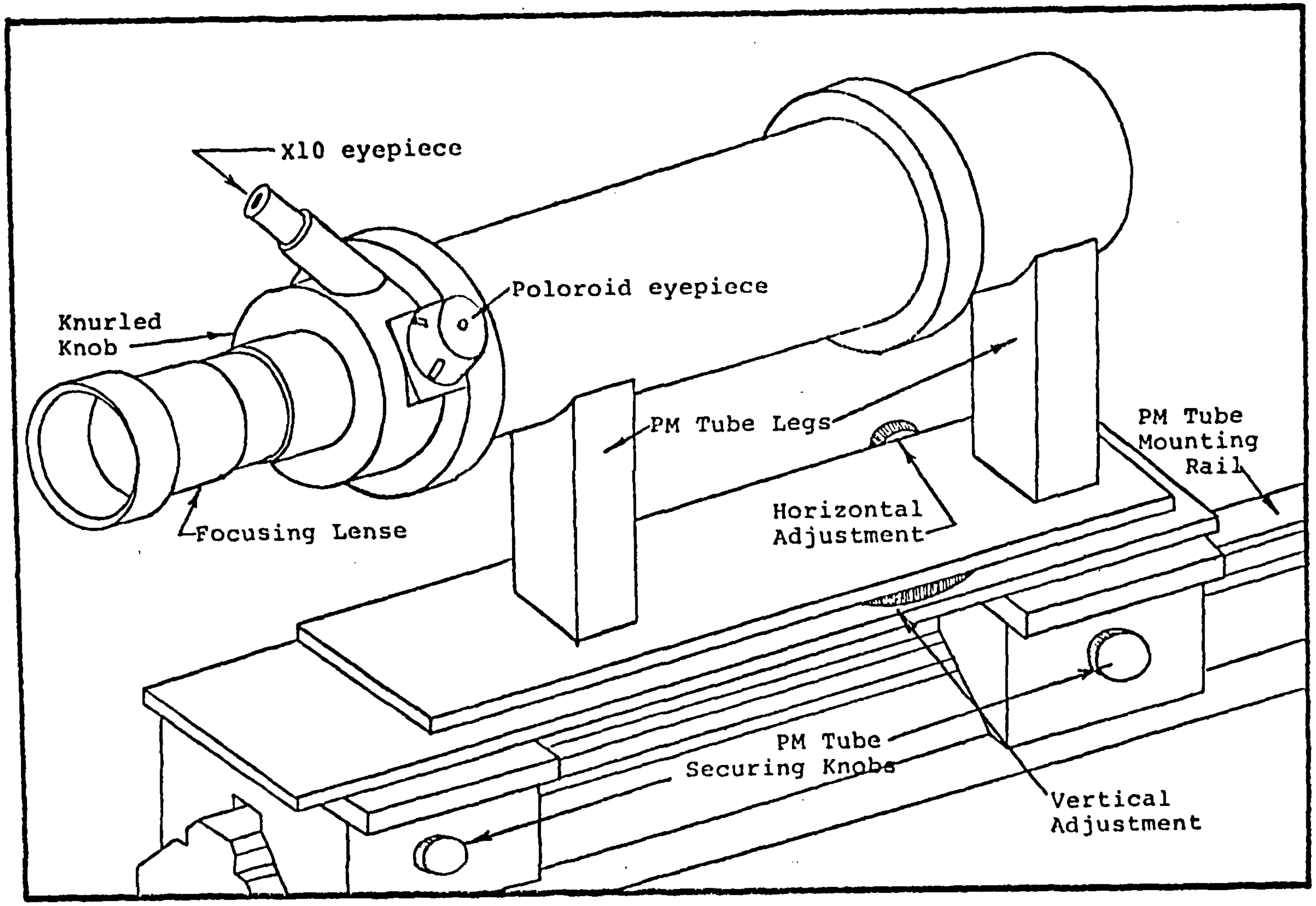
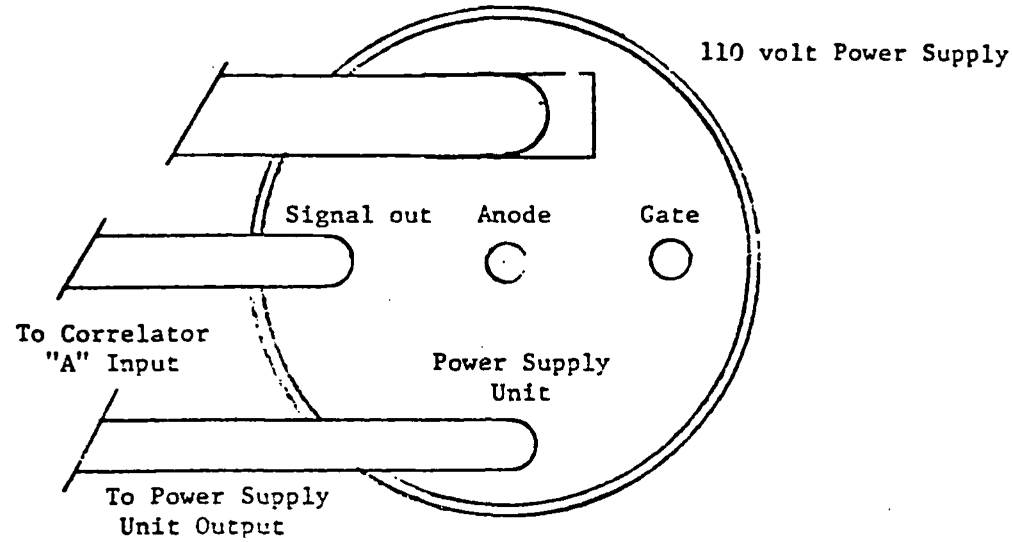


Figure 31 Photo-Multiplier Tube and Adjustment Controls



Rear View of PM Tube

Power Supply Unit

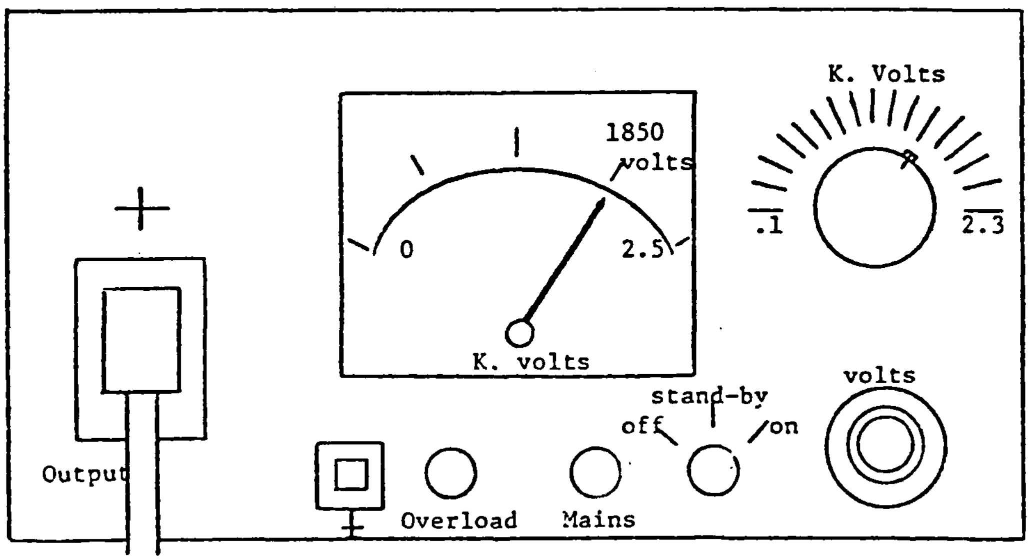


Figure 32 Electrical Connections to Photo-Multiplier Tube

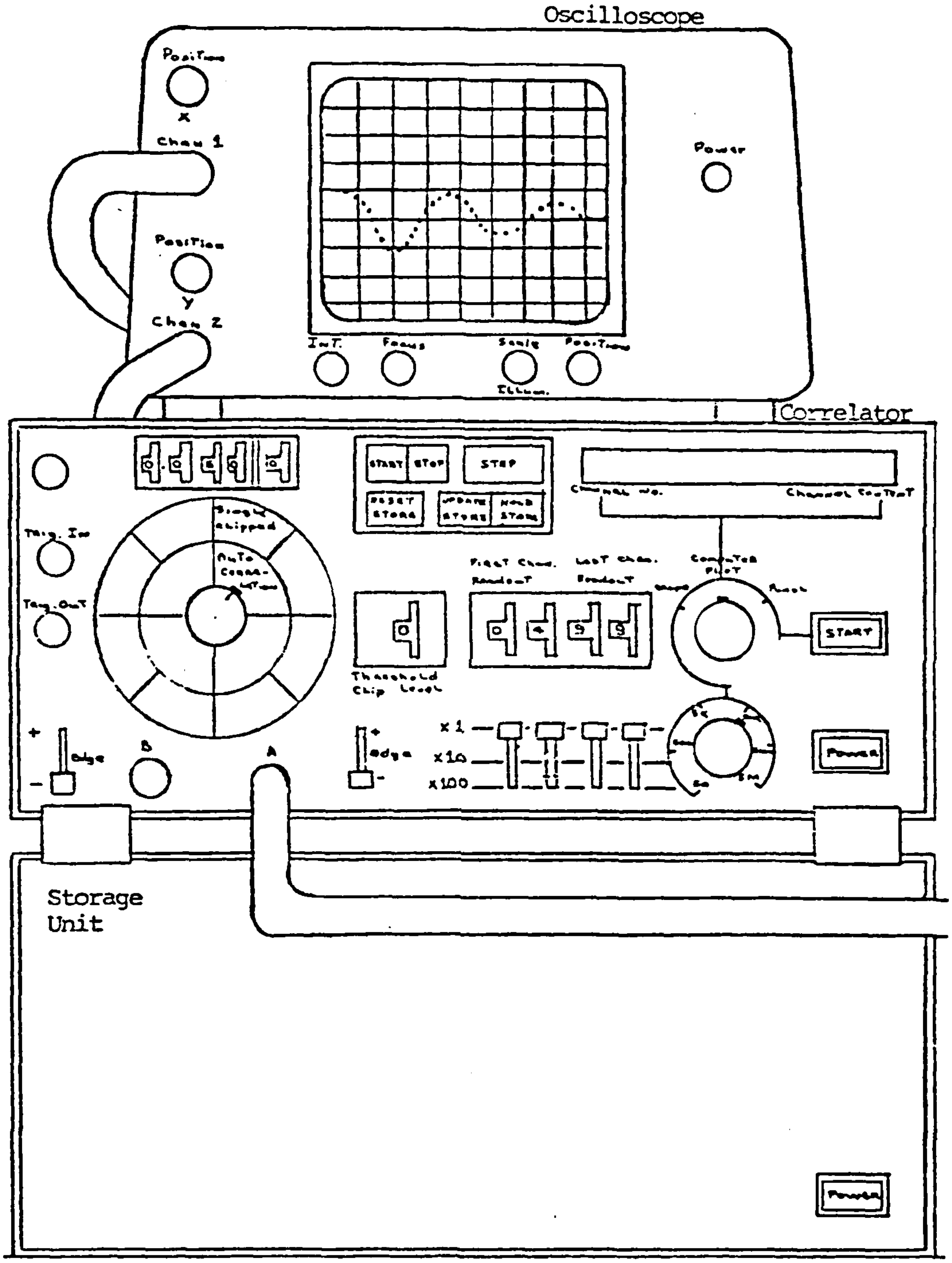


Figure 33 Physical Arrangement of Digital Correlation Equipment

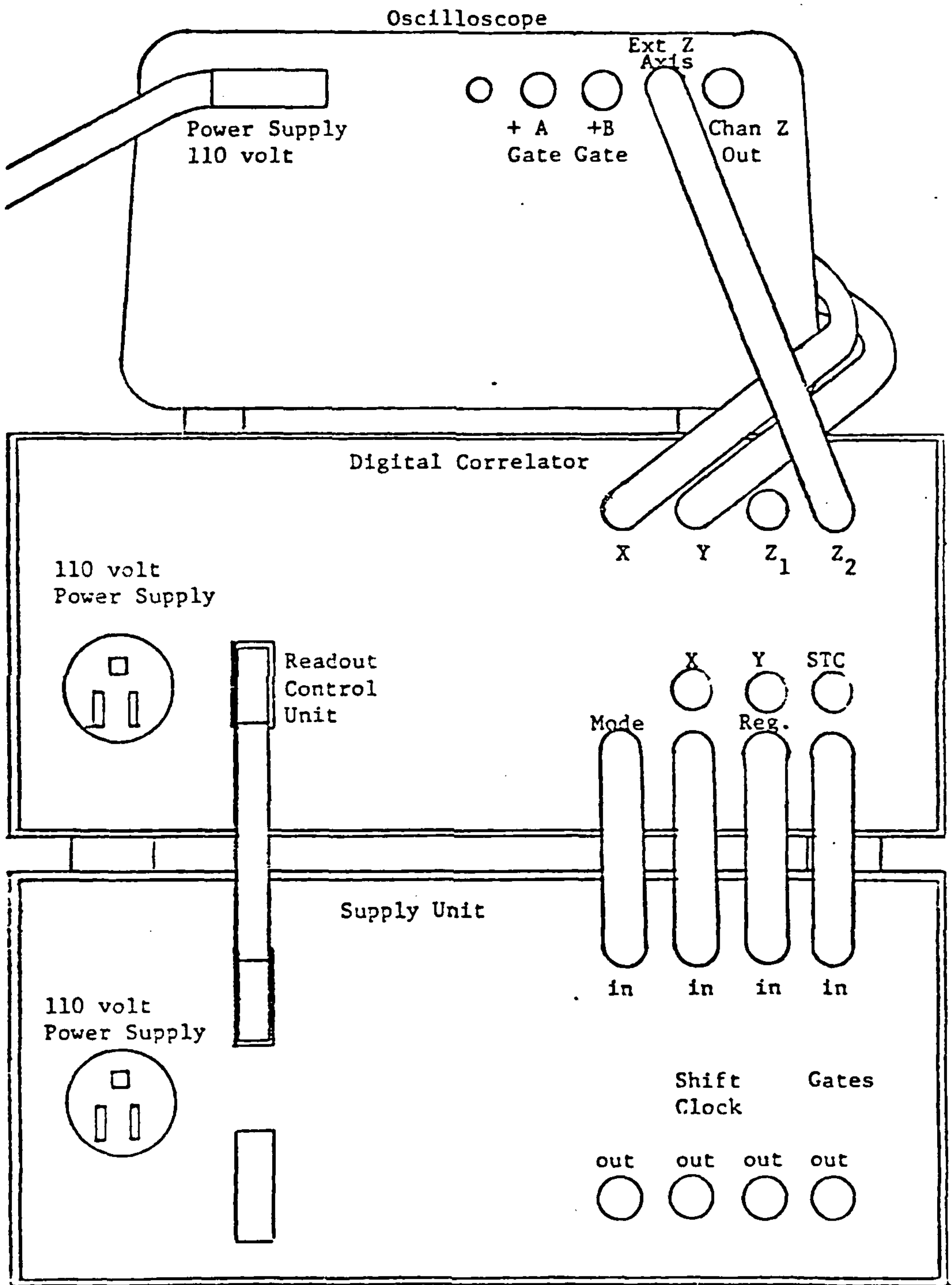


Figure 34 Wiring Connections for Digital Correlation Equipment

Although the helium-neon laser is not very high powered, it is safest to assume that it can cause permanent eye damage if viewed directly. As such, all personnel should be aware of the danger poised and take appropriate care when in the vicinity of the operating laser. Eye protection goggles of the proper type can eliminate the hazard. In the same regards of sensitivity, the Photo-Multiplier Tube is exceptionally sensitive to small amounts of light and is easily and permanently damaged by even low level room illumination. When connected to its power source it should not be exposed to normal room lighting, nor should the laser beam be allowed to shine directly into the Tube.

7. Alignment. The most time consuming and painstaking effort in operating the Laser Doppler Velocimeter is aligning the optics. Without proper alignment the system will not produce a usable autocorrelation function.

   a. The first step is to estimate the flow velocity. This determines the appropriate fringe spacing desired. For relatively low speed flow, less than 40 meters/second, the fringe spacing should be nearly 1.0 E-05 meters. Flow velocities greater than this are not possible in the AFIT Blue Smoke Tunnel;

for other cases refer to ref 12.

b. The fringe spacing for a particular combination of optics and distances is calculated from the following equation:

$$Sp = (Ln * Wv) / Se$$

where the index of refraction of air (1.0) has been assumed and the variables are

Ln -- focal length of focusing lens

Se -- separation of laser beams at the focusing lense

Sp -- interference fringe spacing or the half fringe width

Wv -- wavelength of the laser used (6.328 E-06 meters)

The equation can be inverted if the required fringe spacing for the expected velocity is used and will determine the appropriate focal length for the lense. The fringe spacing can also be calculated by another method. As in Fig 35 measure Ln as the distance from the point of intersection of the laser beams to a vertical surface, and measure Se as the separation of the two laser beams at that wall. This computation should produce the same results as using the previous

$$\text{Two}\theta \approx \frac{Se}{Ln} \qquad Sp = \frac{Ln * Wv}{Se}$$

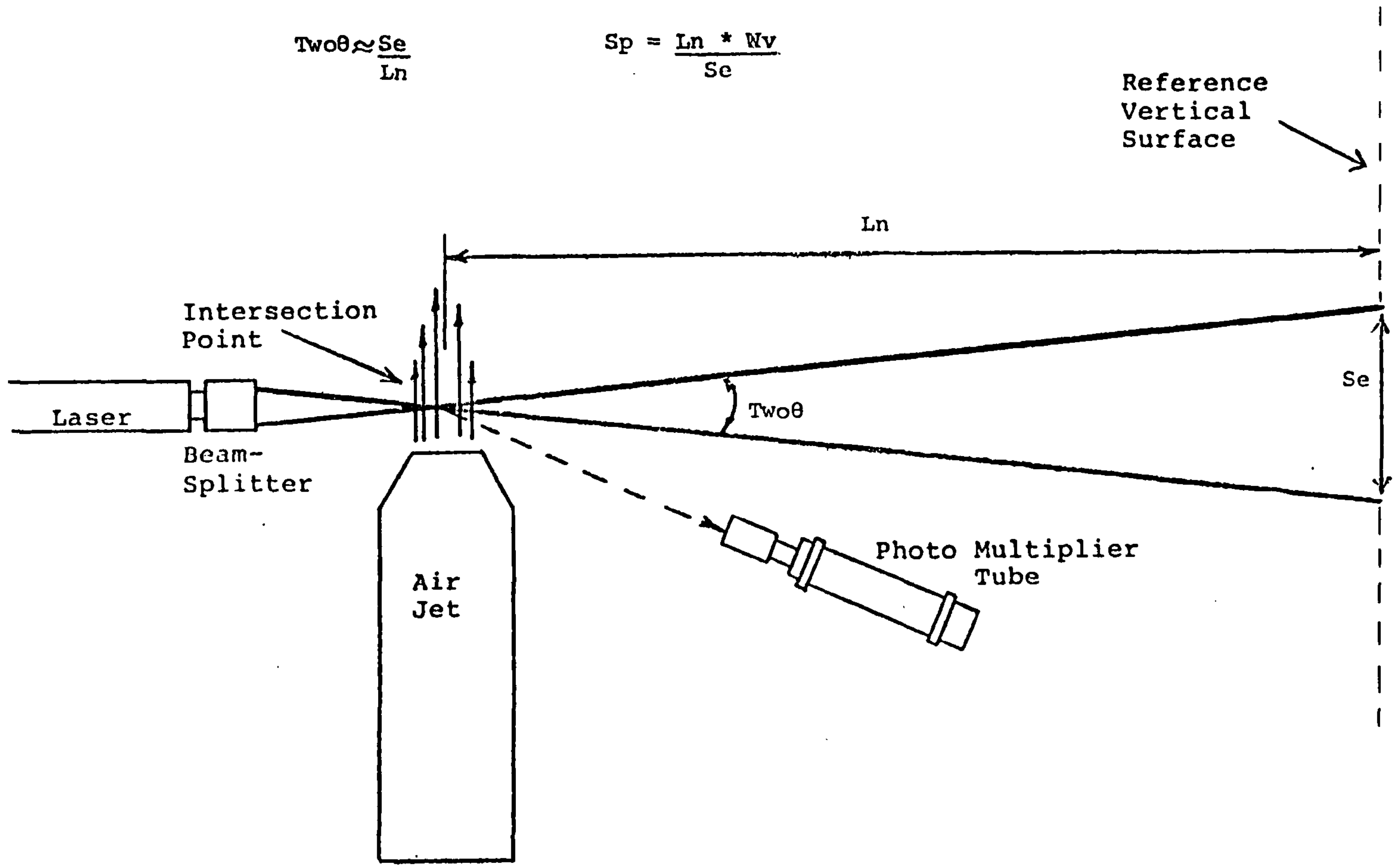


Figure 35 Determination of Fringe Spacing

definitions of the variables, and provides a verification that the laser beams are indeed parallel upon entering the focusing lense, as well as checking the focal length of the lens.

c. The parallel nature of the twin laser beams is controlled by the knurled knobs on the beamsplitter casing. The knob closest to the laser adjusts the separation distance of the beams, while the other knob adjusts the angle between them. The laser must be aligned such that the twin laser beams enter the phase modulator crystal parallel or the doppler shifting of the beams will not be accurate. The best separation of the beams is about 0.02 meters.

d. In order to focus on the probe control volume with the Photo-Multiplier Tube (Fig 36) it may be necessary to contruct a white block that can be placed in the smoke tunnel to reflect the light into the Photo-Multiplier lense. Care must be taken to ensure that the Photo-Multiplier Tube is not powered at this point, as the direct laser light would burn it out. Rough alignment of the tube can be made by looking along the barrel from behind and sighting it in relation to the laser spot

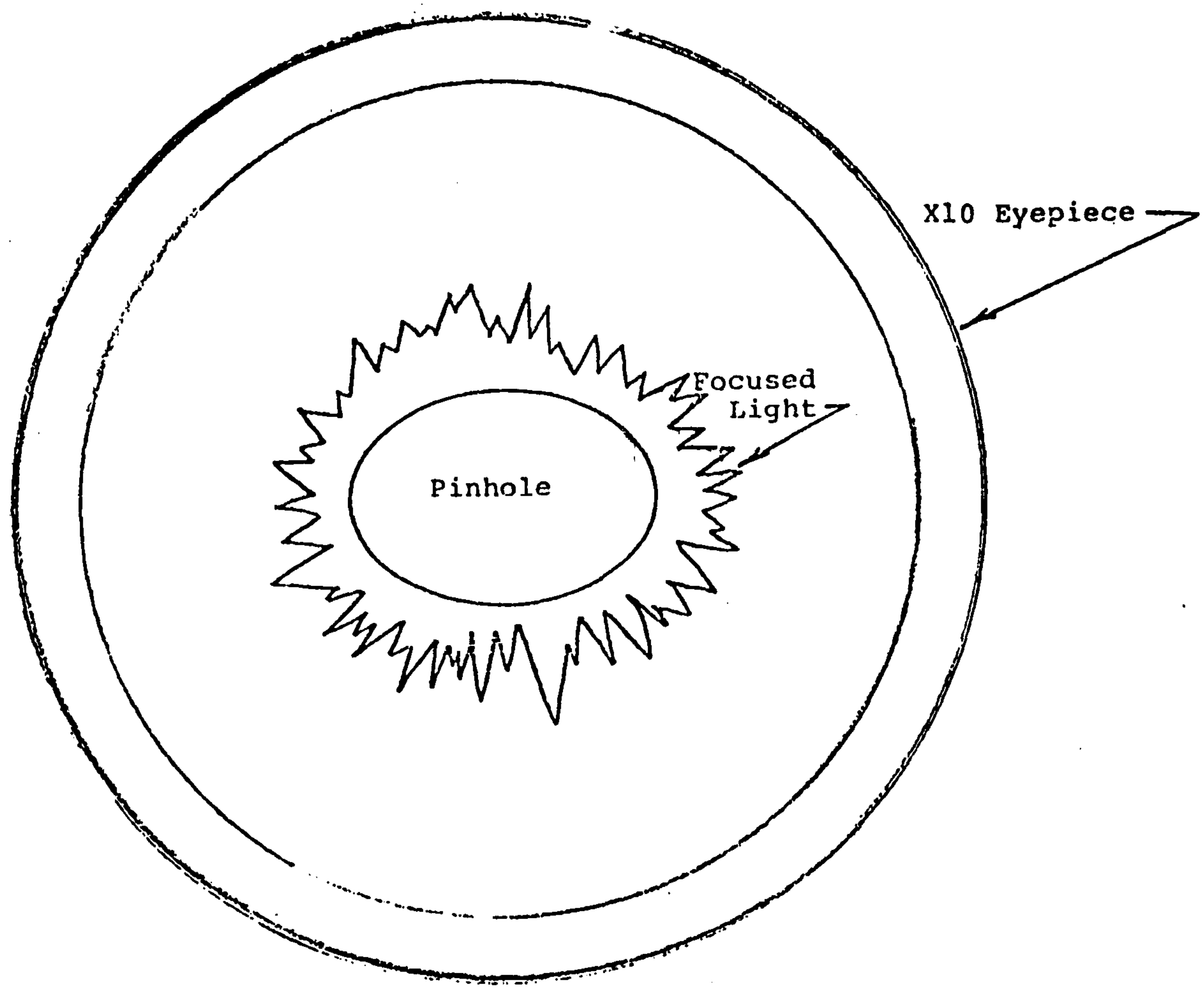


Figure 36 View of Photo-Multiplier Tube Pinhole

on the white block. By looking through the Polaroid eyepiece on the Photo-Multiplier and using the vertical and horizontal controls it is possible to focus the spot from the laser beam intersection on the pinhole, aligned with the cross-hairs in the eyepiece. Once focused, ensure that all knobs and screws are tightened to avoid altering the adjustments.

8. Use of the Phase Modulator. Occasionally flow conditions will be encountered where the Photo-Multiplier Tube and the Digital Correlator are unable to produce an output from which the mean velocity or turbulence intensity can be obtained. This occurs in cases where the fluid flow is either too fast, too slow or too turbulent for the limitations of the equipment. If these conditions are encountered (such as a straight line autocorrlation curve, devoid of peaks and valleys) then it becomes necessary to utilize the Phase Modulator. An example of the expected effect of Phase Modulation use is shown in Fig 37.

9. Measurements. The warm-up period of the equipment is usually about fifteen minutes. Warm-up should be allowed for the Photo-Multiplier Tube power supply, the laser power supply, the Digital Correlator Storage Unit (Power button ON), the Digital Correlator (Power button ON), the

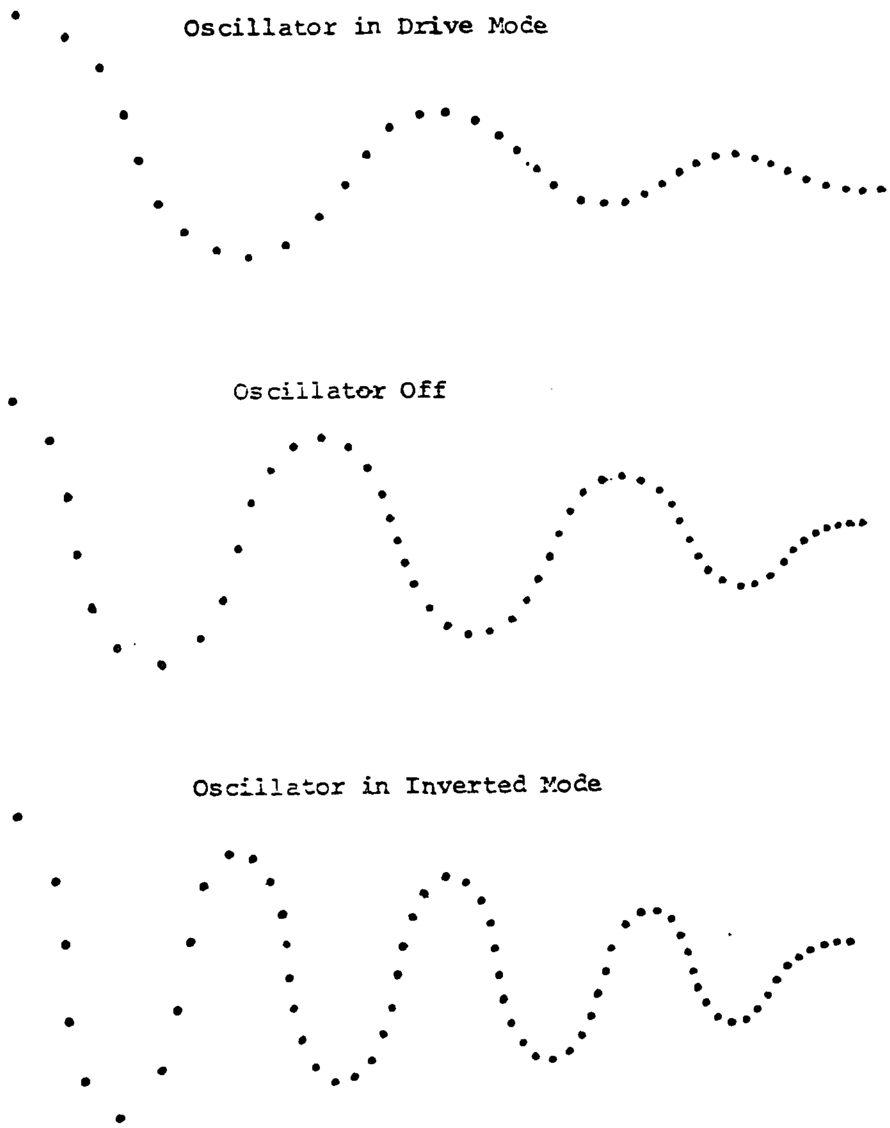


Figure 37 Phase Modulation Effects on Autocorrelation Functions

oscilloscope and the Phase Modulator Drive Unit. All unnecessary lighting in the laboratory should be off. Turn the Photo-Multiplier Tube power knob from Stand-by to ON and press the green start button of the Digital Correlator. (Typical settings on the Digital Correlator are: sample time of 0.05 E-06 seconds, number of samples at 0, output level A, threshold clipping at 0, first channel readout at 4, last channel readout at 99, readout mode on SCOPE for Oscilloscope or CALCULATOR PLOT for use with the computer, number of counts per volt at 50K and the monitor channels at x1). Within seconds a sinoscidal type curve should appear on the display of the oscilloscope. When the desired curve is obtained, push the red STOP button to freeze the display. Then the data for calculating mean velocity and turbulence intensity can be taken, either by hand or with computer control.

APPENDIX C

AUTOMATIC DATA ACQUISITION SYSTEM SETUP AND OPERATION

Before beginning this procedure the equipment described in Appendix B must be set up, but all power supplies must remain turned off. Users should acquaint themselves with operation of the Hewlett-Packard computer before proceeding. A minimal amount of programming knowlege is assumed in the following discussion.

Connecting the Computer.

The Hewlett-Packard 9845B computer is essentially self-contained and ready to be plugged in to an electrical outlet. Into the back of the computer, plug in the 98035A Real Time Clock Card, the 98032A 16-Bit Interface for the 9885M Flexible Disk Drive, and the 9878A Input/Ouput Expander Interface. All other interface cards are plugged into the Expander, including the 98034A Daisy Chain Interface, the 98033A Binary Coded Decimal (BCD) Interface for data transfer from the Digital Correlator and the 98032A 16-Bit Interface for control of the Digital Correlator. The 9872A plotter is connected to the Daisy Chain Interface.

Plug the AMPHENOL 57/30500 plug from the 98032A into the AMPHENOL 57/40500 socket on the electronic translator box (see Appendix D for details of the circuit). Plug the AMPHENOL 17/10250 from the translator into the AMPHENOL 17/20250 socket labeled Remote Control on the back of the Digital Correlator.

Connect the DD 50-P (ITT 8033) plug directly to the AMPHENOL 17/10500 socket labeled Calculator on the back of the correlator. Plug the translator box electrical cord into a electrical outlet, but do not it turn on until after the computer is turned on as it relies upon the computer to determine the internal logic initial states. When all connections have been made, each element of the system may be turned on in the following sequence:

1) Computer
2) Automatic Data Acquisition System Master Power Switch
3) Master Disk Drive
4) Slave Disk Drive
5) 3495A Scanner (Connects with Daisy Chain, so it must be turned on)
6) 9874A Expander
7) Load software as described below
8) Voltage Translation Interface

Loading the Software.

The software developed under this procedure is available in two forms, either on tape cassette cartridge or on flexible disk. Both sets are identical. They are maintained by the Department of Aeronautics and Astronautics at the Air Force Institute of Technology School of Engineering. Locate the desired medium with the program stored on it and load the program as detailed below. In order to check to see if the program is on a medium, use the CAT statement, e.g., CAT":T15" if using a tape in the right hand tape drive, or CAT":F8" if using the lower flexible disk drive.

To load the program stored on tape cassette cartridge:

1. Turn off the computer with the power switch on the right side.
2. Push the button on the keyboard labeled AUTOST down until it clicks.
3. Place the appropriate cassette in the right hand tape transport (T15).
4. Turn the computer on with the power switch.

After the computer warms up for about thirty seconds it will search the tape for a program called "AUTOST" and load it into computer memory. The program is very long and takes about two to four minutes to load. When it has been loaded the computer will begin to run the program automatically.

To load the program from a flexible disk:

1. With the computer system completely on, enter from the keyboard MASS STORAGE IS ":F8"
2. Place the appropriate flexible disk in the lower disk drive (Master).
3. Enter from the keyboard LOAD "DARLA"

Once again, the program is very long and takes several minutes to load into the computer memory. When the loading is complete the green run light in the lower right corner of the cathode ray tube display will go out. Press the yellow RUN key to start the program.

Using the Software.

The program developed in this procedure provides a maximum amount of user interaction with a minimum of required manual input. The program leads a user from step to step, continuously prompting the user with questions, details what activities are underway, presents available options and states what actions must be taken. Each step is self-explanatory, with pauses and waits built-in to the program to allow the user time to make decisions and view intermediate results.

The software is functionally divided into sixteen modules. Each module performs specific tasks, from running the correlator and reading the data to fitting curves to the autocorrelation and storing the final results on disk for permanent access. The names of each module appear at the top of cathode ray tube display when the program is running, arranged according to the assigned softkey value of each. A particular module executes when its softkey is pressed.

Prior to using the program the first time a user should place a blank, unused flexible disk in the upper disk drive and initialize it. Enter INITIALIZE ":F8,1" from the keyboard. The initialization process takes about fifteen minutes as it writes zeroes in every byte on the entire disk (thereby erasing anything previously on it). When the disk initialization is finished, or if it has been done previously, then the program may be continued. The initailized disk is used by the program to store data from the experiments and the description of the airfoil under study. This disk, or a similarly prepared one, must be in the upper disk drive whenever the program is run. The two files on the disk will be "Datem:F8,1" and "Model:F8,1". These files are created by the program under user control by modules "C-File" and "MODEL" as described below. Those two modules should be executed at a users' earliest convenience when running the program the first time. Subsequently both files are used over by the program, until the user desires a change or until the limit of two hundred data points has been reached and a message to that effect is displayed (at which time a continuing file on another disk must be created by using "C-File").

When the program begins running it immediately sets up the necessary data storage for computations, plotting and other tasks, as well as checking the time and thereafter keeping track of it. It asks the user for information regarding the specifics of the Laser Doppler Velocimeter setup being used in the experiment. These inputs are the wavlength of the laser in meters, the focal length of the focusing lense and the separation distance of the twin laser beams at the focusing lense. Thereafter any of the modules described below will execute and perform the desired tasks when the corresponding softkey displayed on the cathode ray tube display is pressed.

A. "CORREL" This module handles clearing of the Digital Correlator memory and runs the autocorrelation for ten seconds. The run time can be altered by changing the variable 'Total' in subroutine "Run_correlation" to the integer value of seconds desired. No input is required.

B. "READ" The second module performs the data transfer from the Digital Correlator to the computer. It requests from a user the sample time set on the Digital Correlator and the modulator frequency set on the Phase Modulator. These are necessary in any calculations to be done with the data. The data is read from the Digital Correlator into the array 'A' to be used throughout the entire program. The time that the data was read into the computer is recorded in order to tag particular data points. The data is quickly plotted and the graphics displayed on the cathode ray tube for five seconds. This allows a user to view the autocorrelation and determine if the data are valid and satisfactory.

C. "LOCATE" This module is used before or after running the correlator and reading the data. It is a means by which particular data points are identified to the computer. It relies upon the module "MODEL" described below. A graphical display of the airfoil in the test section of the smoke tunnel appears and the user is asked to locate the coordinates of the point at which Laser Doppler Velocimetry data is currently being taken. Locating the point is either by moving the displayed cursor with the left, right, up and down arrows, or by entering the actual coordinates of the point in millimeters measured from the lower left hand corner of the test section. The location information is used by the program to develop a velocity profile about the airfoil in the module "RESULTS."

D. "STORE" This module is part of the data base management system developed for this program. It writes all of the information pertaining to a particular Laser Doppler Velocimetry data point onto a data storage disk (over two thousand bytes) for later retrieval by other modules or use at a later date. The data storage area must be prepared first, using module "C-File" and there can only be one data storage area per flexible disk. However, each data storage area or file holds up to two hundred Laser Doppler Velocimetry data points, and usage of the data points later for module "RESULTS" is independent of how many disks are used to store data points from the same experiment.

E. "RESULTS" Probably the last module to be used in an experiment, this produces three plots on the 9872S plotter. Each plot appears the same, as a scale drawing of the test section of the smoke tunnel with the airfoil being tested in place.

This display is readily adaptable to other test environments with minor modifications to the software or can be used as is if a relative origin in the new test environment is kept in mind. On two of the plots are plotted the relative magnitudes of the one-dimensional mean velocity and the turbulence intensity, respectively. The third plot has the actual numerical values of velocity and turbulence listed at the location of the data point. The module will plot all values for a specific angle of attack (the identifying factor), independent of how many separate flexible disks those points are stored on.

F. "Screen" and "Plotter" These short modules merely determine where the results of computations and curve-fitting will be printed, the former being the cathode ray tube graphics and the later on the 9872S plotter.

G. "Switch" Another very short module, this one allows the user to switch back and forth from the cathode ray tube graphics display to the character display.

H. "CRV-FIT" Perhaps the longest of all the modules, it is here that most of the calculations are done. This module should be called only after a sastisfactory autocorrelation has been transferred to the computer. This module locates the local maximums and minimums of the autocorrelation data. These are used to produce polynomial curve-fit and then unskew the data. From the unskewed data the mean velocity and turbulence of the fluid flow are computed. The curves are plotted and all relevent data printed on a single page for minimal hardcopy storage of the information.

J. "PICKOFF" This module is for use when the autocorrelation has unavoidable noise, such as spikes, in the data. The routine provides graphical displays prompting the user to eliminate the bad data points, pick off the data to be used as the unskewing curve-fit and locate the maximums and minimums describing the mean velocity and turbulence.

K. "SEARCH" This is the heart of the data base management for this program. It very carefully directs and leads a user through operations to purge old data points that were bad or no longer needed, to reprocess old data to have another look at it, to list out a common set of data points, to dump out all the information on a flexible disk (an extremely large amount of paper is generated), and to summarize all of the data points on a particular disk. Each activity is independent and a user can escape at almost any point.

L. "ENTRY" This module is dedicated to past experiments. It is intended solely for entering autocorrelation data by hand from previous experiments, so that the present software can be used to process it. Once the data is entered, any of the other modules may be used.

M. "C-File" In order to have a place to store all of the voluminous information generated by this program, a file must be created on a flexible disk (or on more than one). This module creates the proper file for storage of two hundred Laser Doppler Velocimetry data points, and will check to see if an earlier file of the same type is to be destroyed. The decision is always in the hands of the user.

N. "MODEL" The program relies upon physical locations for producing displays of flow fields. This module allows the user to enter a specific airfoil shape under study into the computer memory (and onto the flexible disk), for later use in drawing the smoke tunnel test section, airfoil and flow patterns. A photograph or drawing of the airfoil of interest is placed on the 9872S plotter and using the digitizer sight the shape is traced into the computer. The user only must orient the computer as to the chord of the airfoil, and thereafter the computer can vary the angle of attack of the airfoil at the discretion of the user. This file, "MODEL:F8,1", must be present on all flexible disks used for data storage, but once made, can be copied from one flexible disk to another.

O. "Simulat" To acquaint the user with the software without the need for setting up and running the smoke tunnel and entire Laser Doppler velocimeter, this module was developed. It simulates with fourier series the autocorrelation as received in previous Laser Doppler Velocimetry experiments. It is operated in place of the "CORREL" and "READ" modules. All other functions are the same.

P. "HALT" The last module merely shuts down the program, clearing out storage and removing displays and graphics.

APPENDIX D

INTERFACING ELECTRONICS

Communication between the Laser Doppler Velocimeter and the Automatic Data Acquisiton System requires electronics to transfer the signals and translate the voltages. Two standard Hewlett-Packard interfaces are the basis for communication with and control of the Laser Doppler Velocimeter Digital Correlator by the Automatic Data Acquisition System computer. These interfaces are the Hewlett-Packard 98033A Binary Coded Decimal (BCD) Interface and the Hewlett-Packard 98032A 16-Bit Interface. The former is used to transfer data from the Digital Correlator to the computer, while the later is used to perform control functions to operate the Digital Correlator by the computer.

The free end of the 98033A is directly connected the the Digital Correlator with a 50-way DD 50-P (ITT 8033) plug matching the 50-way AMPHENOL 17/10500 socket on the back of the correlator. The 98033A interface card end is plugged into the back of the computer or into the 9878A Input/Output Expander which in turn is plugged into the computer. The connections for the free end of the 98033A are given in Table I, listing the signal on the line, the color code of the line (wire), the pin number of the plug the line connects to and identification of what each connection does in the correlator. The most significant digit convention varies from the 98033A to the Correlator, as indicated in the table. Hewlett-Packard numbers the digits from left to right, with 1 being the most significant digit. For the Correlator, the most significant digit is numbered 8 (Table III). Each binary coded decimal digit requires four bits of information, thus is a four bit number with the bits labeled D,C,B,A from most significant to least significant. This convention is the same between both pieces of equipment. The bits correspond to powers of two:

D -- 2 cubed = 8

C -- 2 squared = 4

B -- 2 to the first power = 2

A -- 2 to the zero power = 1

Each bit may take on either the value 1 or 0. The possible combinations allowed are:

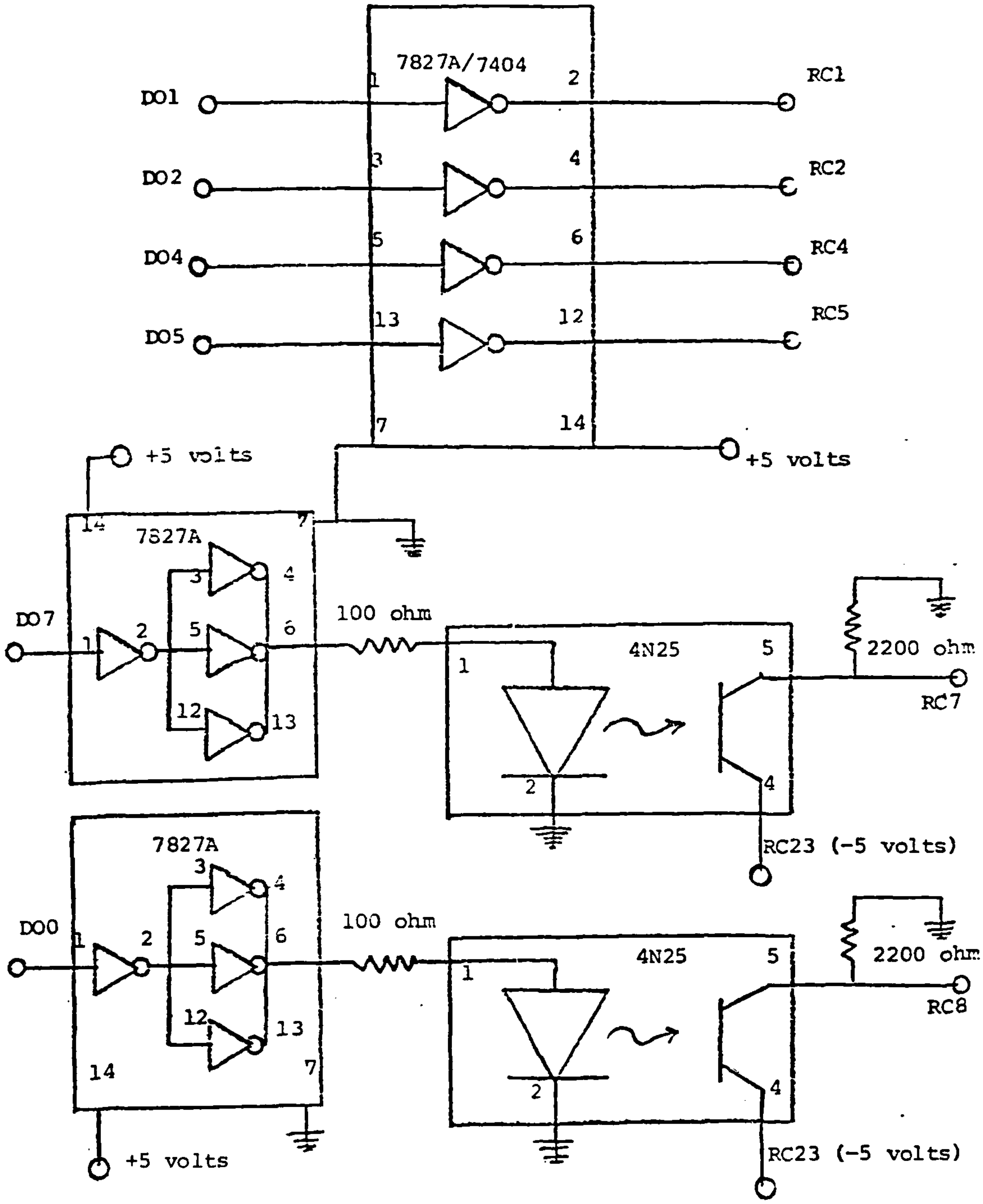
D	C	B	A	value
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9

The Digital Correlator has a short-eight digit output, actually only seven and a half digits (the most significant digit is 8, the most significant bit is B, thus MSD/MSB is 8B). The largest number possible for output from the Digital Correlator is then 39,999,999. Seldom, if ever, will the channel contents be that high.

The differences in voltage requirements for the Remote Control of the Digital Correlator makes essential the use of a voltage translation circuit between the 98032A and the Remote Control plug. The plug is a standard Amphenol 25-way 17/20250. Connecting to it is done with an AMPHENOL 17/10250 socket. The socket is part of the translation circuit. The 98032A is connected to the translation circuit via an AMPHENOL 57/30500 plug into an AMPHENOL 57/40500 socket. The signals on the various lines of both the 98032A and the Remote Control are described in Table II. The details of the necessary control signals for the Remote Control are listed in Table IV. All signals to the Remote Control pass through electronic buffers in the translation circuit which allows the Digital Correlator to be electronically isolated from the computer when the translation circuit power supply is turned off. In addition, the External Correlator Start and External Correlator Stop lines are electro-optically isolated from the Digital Correlator. This part of the circuit translates the +5 volt, logic 1 signal of the computer into a -5 volt, logic 1 required by the Digital Correlator. The electronic circuit used is shown in Fig 38.

The circuit performs in the following manner: DO1, DO2, DO4, and DO5 from the 98032A (Table II) connect to the input pins 1, 3, 5, and 13, respectively of a hex-inverter integrated circuit. Any time a logic 1 appears on the input pins, a logic 0 appears the respective 2, 4, 6, or 12 output pin. The logic 0 signal is electrically a ground voltage, which is what is required to activate the RC1, RC2, RC4 and RC5 pins on the remote control. Thus setting a particular bit on the computer to logic 1 by outputing 2, 4, 16, or 32 respectively causes that particular function on the remote control to execute.

The principle with DO7 and DO0 is similar, with the exception that the voltage must be changed from +5 volts to -5 volts. This is done with the opto-isolators. DO7 and DO0 each connect to pin 1 on two hex-inverter integrated circuits (7827A). To increase the current capability of the output signal from the integrated circuit, three of the inverters in each are connected in parallel. The net effect is that a logic 1 on input will result in a logic 1 on output. The outputs are connected through current limiting resistors to pin 1 of the 4N25 opto-isolators. The logic 1 signal (+5 volts) causes the photo-diode in the 4N25 to emit light, thus reducing the elctrical resistance of the photo-darlington transistor beside it in the integrated circuit. The collector of the photo-darlington is then at the same potential as the emitter (-5 volts) and this signal is the one transmitted to RC7 and RC8 respectively. A pullup resistor on the line ensures that the outputs do not float between signals, but are held at ground level. Each integrated circuit is powered and grounded as shown in Fig 38.



Ground Connections to RC25

Figure 38 Electronic Voltage Translation Circuit

TABLE I

CONNECTIONS BETWEEN 98033A BCD INTERFACE
AND THE DIGITAL CORRELATOR OUTPUT SOCKET

98033A Function	Wire Color	Correlator Connection
CTLA	gray	DFLGB (98033A)
DFLGA	white brown gray	11 - output ready
CTLB	white gray	DFLGB (98033A)
DFLGB	white red gray	isolated
Ground	white	50 - GROUND
+5 volts	white orange gray	isolated
Sign 1	white brown blue	GROUND
1D (MSD)	orange	GROUND
1C	red	GROUND
1B (MSB used)	brown	26 - 8B (MSD/MSB)
1A	black	9 - 8A
2D	violet	8 - 7D
2C	blue	7 - 7C
2B	green	23 - 7B
2A	yellow	6 - 7A
3D	white orange	22 - 6D
3C	white red	5 - 6C
3B	white brown	4 - 6B
3A	white black	20 - 6A
4D	white violet	3 - 5D
4C	white blue	2 - 5C
4B	white green	18 - 5B
4A	white yellow	1 - 5A
5D	white black yellow	44 - 4D

TABLE I (continued)

98033A Function	Wire Color	Correlator Connection
5C	white black orange	27 - 4C
5B	white black red	43 - 4B
5A	white black brown	42 - 4A
6D	white black gray	25 - 3D
6C	white black violet	41 - 3C
6B	white black blue	24 - 3B
6A	white black green	40 - 3A
7D	white brown green	39 - 2D
7C	white brown yellow	38 - 2C
7B	white brown orange	21 - 2B
7A	white brown red	37 - 2A
8D (LSD)	white red blue	36 - 1D (LSD)
8C	white red green	19 - 1C
8B	white red yellow	35 - 1B
8A (LSB)	white red orange	34 - 1A (LSB)
10D	white yellow gray	12 - last address
10C	white yellow violet	16 - figures
10B	white yellow blue	17 - addresses
10A	white yellow green	10 - first address

Sign 2, 9D, 9C, 9B, 9A, and Overload (white brown violet, white orange violet/blue/green/yellow and white red violet, respectively) all connect together to GROUND

TABLE II

CONNECTIONS BETWEEN DIGITAL CORRELATOR REMOTE CONTROL AND THE 98032A 16-BIT INTERFACE

Remote Control Function		98032A Function	Wire Color
Readout Start	(RC1)	DO1	white brown
Readout Stop	(RC2)	DO2	white red
Readout Step	(RC4)	DO4	white yellow
Reset Store	(RC5)	DO5	white green
Correlator Start	(RC7)	DO7	white violet
Correlator Stop	(RC0)	DO0	white black
-5 volts	(RC23)	reference	
0 volts	(RC25)	reference	

PFLG and PCTL (gray and white gray respectively) are connected togtner and isolated.

JUMPER 3 on the 98032A Interface Card is installed.

All other wires of tne 98032A are connected togetner to GROUND.

TABLE III

CALCULATOR OUTPUT SOCKET PIN DESCRIPTION

The calculator output socket is an AMPHENOL 50-way type 17/10500. The parallel output binary coded decimal (BCD) digits are numbered from 8 to 1 for most significant to least significant, with the bits labeled D,C,B,A from most significant to least significant.

PIN	FUNCTION
1	Channel contents of digit 5A. > +2.0 volts = logic 1
2	" " " 5C " " "
3	" " " 5D " " "
4	" " " 6B " " "
5	" " " 6C " " "
6	" " " 7A " " "
7	" " " 7C " " "
8	" " " 7D " " "
9	" " " 8A " " "
10	First Address. < 0.8 volts indicates first address
11	Information is Static. < 0.8 volts indicates data ready
12	Last Address. > 2.0 volts indicates last address
13	Readout Busy. < 0.8 volts indicates readout in progress
14	Slow Clock.
15	External Readout Step. 0 volts (GROUND) initiates step
16	Information Figures. < 0.8 volts indicates numerical data
17	Address Figures. < 0.8 volts indicates output address data
18	Channel contents of digit 5B. > 2.0 volts = logic 1
19	" " " 1C " " "
20	" " " 6A " " "
21	" " " 2B " " "

TABLE III (continued)

PIN	FUNCTION						
22	Channel contents of digit		5D.	> 2.0	volts	=	logic 1
23	"	"	" 7B	"	"		"
24	"	"	" 3B	"	"		"
25	"	"	" 3D	"	"		"
26	"	"	" 8B	"	"		"
27	"	"	" 4C	"	"		"
28	no function						
29	no function						
30	Channel address unit digit		B.	> 2.0	volts	=	logic 1
31	"	"	" D	"	"		"
32	"	"	ten digit B	"	"		"
33	"	"	" D	"	"		"
34	Channel contents of digit		1A.	"	"		"
35	"	"	" 1B	"	"		"
36	"	"	" 1D	"	"		"
37	"	"	" 2A	"	"		"
38	"	"	" 2C	"	"		"
39	"	"	" 2D	"	"		"
40	"	"	" 3A	"	"		"
41	"	"	" 3C	"	"		"
42	"	"	" 4A	"	"		"
43	"	"	" 4B	"	"		"
44	"	"	" 4D	"	"		"
45	no function						
46	Channel address unit digit		A.	> 2.0	volts	=	logic 1

TABLE III (continued)

PIN	FUNCTION
47	Channel address unit digit C. > 2.0 volts = logic 1
48	" " ten digit A " " "
49	" " " C " " "
50	GROUND (0 volts)

TABLE IV

REMOTE CONTROL PIN DESCRIPTIONS

The remote control is accessed through an AMPHENOL 25-way plug type 17/20250. Pulsed signal voltages are sufficient to perform the remote control functions.

PIN	FUNCTION
1	External Readout Start. 0 volts (GROUND) initiates start
2	External Readout Stop. 0 volts initiates stop
3	Readout Busy. 0 volts shows readout in progress
4	External Readout Step. 0 volts steps to next channel
5	External Reset Store. 0 volts clears memory
7	External Correlator Start. -5 volts starts correlation
8	External Correlator Stop. -5 volts stops correlation
23	-5 volt reference supply (20 milliamp max current)
25	GROUND (0 volts)

All other pins are not utilized or have no function.

VITA

Captain David L. Weyland was born at Keflavik Air Force Base, Iceland, in 1955. He graduated from Roy J. Wasson High School, Colorado Springs, Colorado, in 1973. He attended the University of Colorado, Boulder, Colorado until 1975, whereupon he transferred to the University of Miami, Coral Gables, Florida. He was awarded a Bachelor of Science in Applied Physics in 1977. Upon graduation he was commissioned a Second Lieutenant, United States Air Force, through the Air Force Reserve Officer Training Corps. He entered active duty in October 1977, and was stationed at the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, where he served for three years as a Nuclear Criteria Scientist studying the survivability of United States space systems in wartime environments. In the winter of 1980 his application for Post Graduate Training was approved and in June of that year he commenced an eighteen month program at the Air Force Institute of Technology studying Graduate Astronautical Engineering.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A general Automatic Data Acquisition System dedicated to a broad range of experiments is used to operate the Digital Correlation signal processing equipment of a Laser Doppler Velocimeter, transfer data from the correlator into the Automatic Data Acquisition System computer and perform computations with the information. The Laser Doppler Velocimeter is used to acquire vast quantities of velocity and turbulence intensity information describing turbulent fluid flow about two dimensional airfoils. Integration of the velocimeter

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) with the computer increases the capability of the system to perform large scale fluid dynamic studies.

The necessary electronic interfaces, control functions and computational software were developed to provide a fully operational computerized laser velocimetry system while avoiding the exclusive dedication of a sophisticated computer to the experiment. The system was tested during actual experimental operations to validate the techniques employed. Data was collected in an experiment examining the effects of constant area mixing ducts with ducted ejector airfoils. Results of the computational techniques employed herein were validated by separate manual effort conducted by other experimenters.

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