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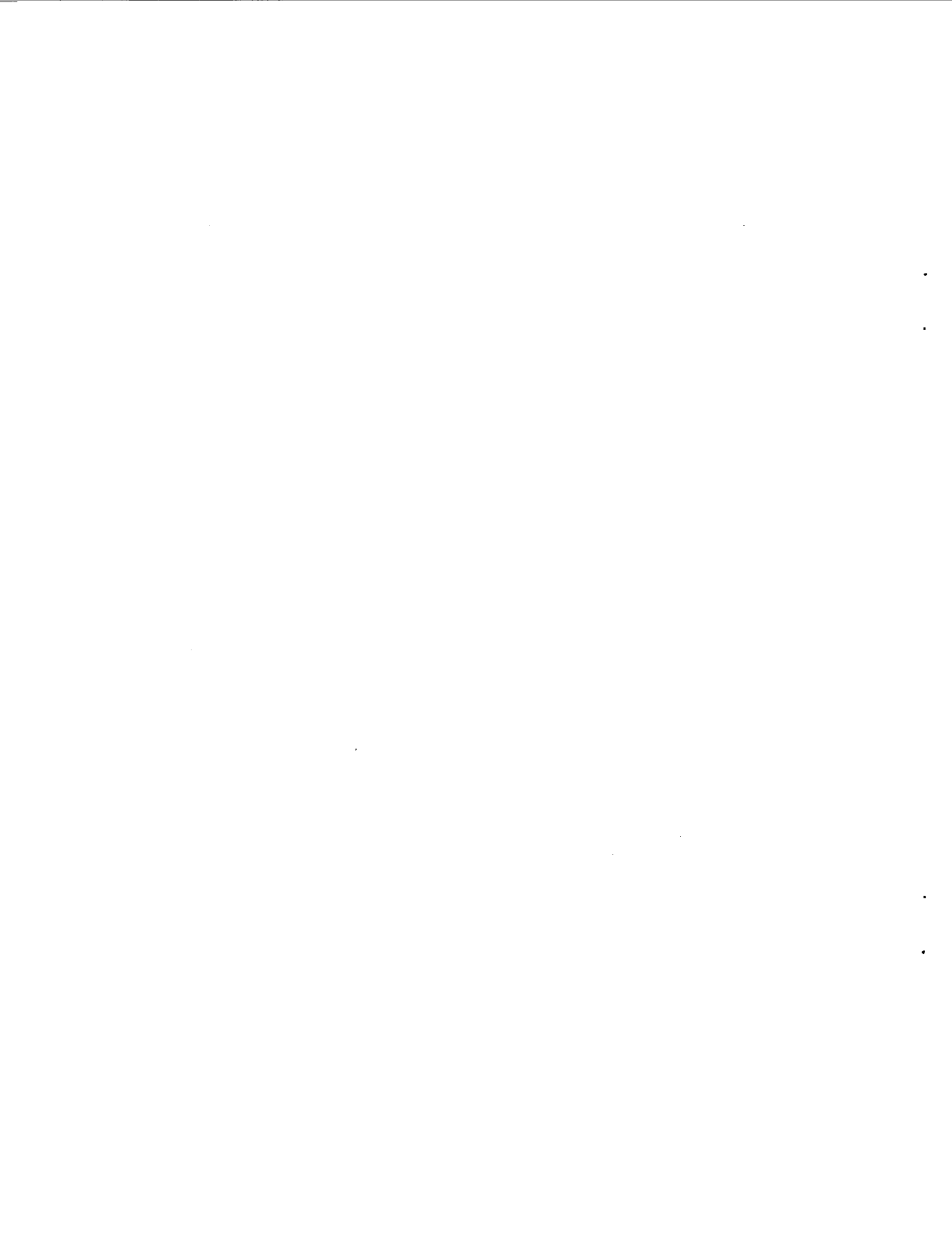
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Summary

A three-component dual-beam laser-velocimeter system
has been designed, fabricated, and implemented in the
7- by 10-Foot Wind Tunnel at NASA Ames Research
Center. The instrument utilizes optical access from both
sides and the top of the test section, and is configured for
uncoupled orthogonal measurement of the three Cartesian
coordinates of velocity. Bragg cell optics are used to
provide fringe velocity bias. Modular system design
provides great flexibility in the location of sending and
receiving optics to adapt to specific experimental
requirements. Near-focus Schmidt–Cassegrain optic
modules may be positioned for collection of forward or
backward scattered light over a large solid angle, and may
be clustered to further increase collection solid angle.
Multimode fiber optics transmit collected light to the
photomultiplier tubes for processing.

Counters are used to process the photomultiplier signals
and transfer the processed data digitally via a buffered
interface controller to the host MS-DOS computer.
Considerable data reduction and graphical display
programming permit on-line control of data acquisition
and evaluation of the incoming data. This paper describes
this system in detail and presents sample data illustrating
the system capability.

Background

Since its introduction in the late 1960s, the laser Doppler
velocimeter (ref. 1) (LV) has seen increasing application
to the study of aerodynamic phenomena. The LV
provides a noninvasive measurement capability which is
critical for the study of many phenomena. The dual-beam
or differential-Doppler configuration of the instrument
(ref. 2) has become particularly popular, and small-scale
turnkey instruments may be purchased from several
commercial suppliers. While several new techniques offer
increased potential for velocity measurement within a
plane (refs. 3 and 4), the LV is still a very important
instrumental capability for any aeronautical research
facility.

The NASA Ames 7- by 10-Foot Wind Tunnel is a low-
speed wind tunnel with a long history of aeronautical test
activity throughout its 50 years of operation. It presently
serves as a pilot tunnel for National Full-Scale Aero-
dynamics Complex. Because of the low cost of operation
of this facility (as compared to the large tunnels of the
National Full-Scale Aerodynamics Complex) it is well
suited for experiments which examine aerodynamic
phenomena in detail. LV is an important experimental
tool in the execution of these types of experiments.

Several LV systems have been used in the facility
previously, including two-component and three-
component confocal-backscatter-zoom systems, and a
three-component fixed-focus off-axis backscatter system.
Because of the long (approximately 2-meter) range
requirement, commercial systems were not available and
these instruments had to be internally developed. Each of
these systems utilized optical access from only one side
of the test section and required a coupling of two channels
to resolve the cross-stream component of velocity.
Because of this (rather strong) coupling, measurement
errors inherent to the technique were strongly amplified
for the cross-stream measurement. These errors clearly
compromised turbulence measurements and even raised
some questions about the mean velocity measurements in
regions of high turbulence or velocity gradients. Further-
more, these systems experienced low data rates due to the
backscatter mode of collection, and several required a
complex zoom calibration to accommodate varying fringe
spacing as the probe volume was zoomed along the
optical axis.

Based on experience with these previous systems, a new
instrument has been designed with particular attention to
improving on the shortcomings of its predecessors.
Because the facility offers optical access from both sides
as well as the top of the test section, it is possible to
operate with forward scatter collection for the streamwise
(u) and vertical (w) velocity components. Furthermore,
direct orthogonal measurement of the cross-stream (v)
component with off-axis backscatter collection is pos-
sible. The zoom feature must be eliminated for direct
orthogonal measurement of three components, to permit
the confocal alignment of the two orthogonal probe

volumes. While this increases the bulk of the instrument, it simplifies the calibration requirements. The details of the design of this instrument are presented in the following sections, along with a description of several sample experiments and data acquired.

Instrument Configuration

Facility

The NASA 7- by 10-Foot Wind Tunnel was the first experimental facility built at Ames Research Center. It has been upgraded to improve flow quality and acoustic testing capability. It is a closed loop tunnel with a 7- by 10- by 20-foot test section. The 1,100-kw single fan drive and 14 to 1 contraction ratio provide a maximum dynamic pressure in the test section of 190 psf. A turntable and scale system permit model positioning and global force and moment measurements. The test section, control room, and adjacent mezzanine work area are all enclosed in a pressurized containment building. This design permits removal of the test section walls for open jet operation.

Two features are of particular importance in the design of the LV:

1. The test section is accessible from both sides as well as the top. Access windows may be installed anywhere along the streamwise length of the test section. The presence of the tunnel balance beneath the test section precludes optical access from below.

2. A linear bearing traverse runs the entire streamwise length of the top of the test section.

Sending Optics

Several factors contributed to the selection of the optical layout of the instrument. First, it was important to avoid the errors associated with a strongly coupled measurement of the cross-stream component. This suggested the use of a vertical optical axis coming in from the top of the test section to measure the cross-stream component directly.

Second, it was desirable to operate in a forward-scatter mode whenever possible. Scattering intensity is uniformly stronger in the forward-scatter mode (as compared to backscatter), and may be orders of magnitude greater, depending on particle size and laser wavelength. However, it should be noted that the location of the collector is always limited by its ability to image the probe volume without blockage from some part of the model. Many times backscatter operation is the only way to access the region of interest. Because the turntable and scale systems

installed in the floor precluded the installation of receiving optics below the test section, backscatter collection was necessary for the vertical optical axis (cross-stream velocity). However, it is often possible to operate in a forward-scatter mode for the LV channels measuring the streamwise and vertical velocity components.

Third, collection of scattered light at some angle slightly removed from the direct back or forward directions (i.e., off-axis) greatly improves the signal quality. When the probe volume is imaged with limited aberration to the plane of the photodetector, a spatial filter (pinhole) of appropriate diameter may be placed in this image plane to reject nearly all the collected light (optical noise) originating outside the probe volume. Off-axis collection is uniformly better than on-axis with respect to efficient spatial filtering, and becomes particularly important if one wishes to measure close to model surfaces where light scattered from the model surface can overpower the Doppler signal by several orders of magnitude.

Factors one and two in combination impose the requirement for a large, rigid frame which partially surrounds the wind tunnel and provides a mounting base for both the sending and receiving optics. The vertical and streamwise component sending optics may be positioned on one side, with forward-scatter receiving optics mounted on the opposite side. The cross-stream velocity component sending and receiving optics are all mounted to the top of the frame above the test section. These optics must all be held in strict relative alignment to ensure that the horizontal and vertical probe volumes remain coincident, and that the collectors (with accompanying spatial filters) remain aligned on the probe volume. This is a rather stringent design requirement for the frame and demands attention to the stiffness of the frame structure as well as to any vibrational forcing functions which would cause deflections. The rigid frame must also be translated throughout the desired range of motion for the probe volume, so it must be relatively lightweight.

Finally, a general utility instrument must be adaptable to many different model configurations. As mentioned above, backscatter operation is often the only way to access an enclosed region of the flow. This requirement suggested a modular design with the capability of operating two sending channels from either side or the top of the wind tunnel, and with removable collector modules that could be positioned as needed on the rigid frame to best image the scattered light.

Figure 1 identifies the various components of the instrument. Details of the beam manipulation optics are shown in figure 2. A horizontal and a vertical optical axis provide direct orthogonal measurement of all three

velocity components. (For measurements close to a model surface, the optical axis must be tilted to provide grazing incidence for the adjacent laser beam. This induces a slight degree of coupling between the horizontal and vertical axis channels.) Collectors may be positioned to receive either forward-scattered or backscattered light from the horizontal optical axis laser beams. The vertical axis collector operates in backscatter mode only. Collectors for both the vertical and horizontal axes are located off axis to reduce noise induced by scattering from model surfaces. The rigid frame is designed for maximum stiffness with minimum weight. This is accomplished by using thin-wall square steel tubing. A welded rectangular frame mounted horizontally above the test section provides good torsional stiffness, with vertical beams hanging from either side to support the horizontal axis sending optics and collector.

The system may easily be configured in a variety of ways. The blue (488-nm) and green (514-nm) lines of a 5-watt argon ion laser are used. A 50 percent beamsplitter divides each of these beams, and the resulting four beams are each split by a parallel-prism beamsplitter. This results in a total of four dual-beam LV channels. Sending optics are configured to provide green and blue beam pairs on both the horizontal and vertical axes. This permits the redundant measurement of the streamwise velocity component, if desired, or the redundant channel may simply be blocked. The vertical legs of the frame are interchangeable so that the laser beams may enter either side of the test section. Perhaps the single feature of the system that most contributes to flexibility is the modular collector design, described in the following section.

Additional details of the system design include a Galilean type beam collimation telescope located in front of the color separation prism. This adjustable scope expands the beam diameter by a factor of 2 (to reduce the probe volume diameter) and permits focusing of the beam waist to match the beam crossing (probe volume) location. The telescope may be adjusted to locate the waist of only one beam pair at the probe volume. Because of dispersion effects and unequal path lengths for the two optical axes, the other beam pair waists will not coincide with the probe volume. A single dispersion prism is used to separate out the green and blue laser lines. A beamsplitter and mirrors are used to separate out up to four dual beam measurement channels as described above. Focusing lenses are used to focus the beams to an intersection in the probe volume.

Design prediction optical specifications (from Gaussian beam propagation analyses) for the beam focusing system are presented in table 1. These data are for the beam telescope adjustment that places the vertical-axis green beam pair waist at the probe volume. The diameter and number of fringes are nearly uniform for each probe volume. Variations in wavelength and path length result in a beam waist offset as indicated for the other three beam pairs. Fortunately, for the worst case this is less than 10 percent of the Rayleigh range; therefore, fringe curvature is not a problem. The beam waist diameter and fringe spacing were measured for the two vertical axis probe volumes and are included for comparison. A spinning slit beam profiler was used to measure the waist diameter. Agreement with the predicted values is not particularly good. The laser output beam diameter and divergence specifications were used in the design predictions and probably do not accurately represent the actual laser performance. Additionally, these measurements were taken with the laser cavity aperture wide open, and the 488-nm output was likely not TEM_{00} mode. Fringe spacing as determined from a velocity calibration is also included for the vertical 514-nm channel and shows very good agreement with the design prediction.

Table 1. Beam focusing system optical specifications

| | Design prediction | | | | Measured vertical axis | |
	Vertical axis		Horizontal axis			
Velocity component[a]	u	v	u	w	u	v
Wavelength (nm)	514.5	488	514.5	488	514.5	488
Probe volume diameter (microns)	325	317	318	308	263	389
Fringe spacing (m/sec/MHz)	17.6	16.7	17.2	16.4	17.64	
Number of fringes	18.5	19.0	18.4	18.8		
Rayleigh range (mm)	162	162	154	153		
Waist offset (mm)	0	–8.6	–14.8	–22.8		

[a]Velocity components in tunnel coordinates, u (streamwise), v (cross-stream), and w (vertical).

Collection Optics

The previous discussion identifies the need for compact light-collection optics that can be easily positioned to image the probe volume from a variety of forward- or backscatter directions. It is important to maximize the collection solid angle for these optics to provide adequate light for the photodetectors, particularly if operating at long range or in backscatter mode. Experience suggests a collection f-ratio (distance to probe volume divided by collector aperture) of about 10. For this instrument, where the collector must be approximately 2 meters from the probe volume, an aperture of 200 mm is required. A lens optic of this size would require custom design and fabrication.

In recent years, advances in manufacturing techniques (for the aspheric corrector plate) have provided a variety of commercially available Schmidt–Cassegrain telescopes with apertures up to 350 mm. These systems use inexpensive spherical figures for the primary and secondary mirrors and a weak aspheric lens (Schmidt corrector plate) placed at the upper end of the tube to correct the resulting spherical aberration. While these units are designed for wide field imaging performance at infinite conjugate ratio, a methodology has been developed (ref. 5) to adapt them for on-axis imaging at conjugate ratios near unity. An example of a modified telescope is shown in figure 3. The modification typically requires replacement of the secondary mirror and/or repositioning of the three optical elements.

The modified Schmidt–Cassegrain collector has several attractive features:

1. The imaging performance of a properly modified system is nearly diffraction limited. This permits very efficient spatial filtering of the collected light to improve the signal-to-noise ratio (S/N) (particularly for small probe volumes).

2. Large aperture systems may be purchased at a fraction of the cost of custom designed refractive optics, and adapted with low-cost modification.

3. Because the high-power elements in these systems are reflectors, chromatic aberration is virtually nonexistent. This permits two-color operation with no loss of imaging (spatial filtering) capability.

4. The folded Cassegrain design provides a very compact optical package. The telescope tube assembly provides for solid mounting and has a built-in focusing adjustment.

There are also some drawbacks to the use of modified telescope optics. Some care must be taken to perform the modification correctly if efficient spatial filtering is desired. The limiting aperture for low conjugate ratio

operation shifts from the corrector plate to the primary mirror at the rear of the assembly, which increases the spacing to the limiting aperture and reduces collection solid angle. Also, the central obstruction of the secondary mirror blocks the central portion of the scattering cone and can significantly reduce the collection solid angle. The two light reduction effects become particularly acute at lower collection f-ratios.

Two different telescope designs have been modified to perform the collector function on this instrument. These include a 200-mm aperture f-10 telescope and a 250-mm f-6.3 scope, denoted as configurations 1 and 2, respectively. (These f-numbers apply to the infinite conjugate design specification for the scope and denote the combined system focal length divided by the corrector plate aperture.) The frame geometry is such that the operating range of 1.9 meters is the same for both the horizontal and vertical optical axes. Table 2 presents a summary of the specifications for these modified collectors.

Table 2. Collector system specifications

Collector configuration	1	2
Range, corrector plate to probe volume (m)	1.900	1.900
Corrector plate		
Diameter (m)	0.200	0.254
Thickness (m)	0.00452	0.0054
Refractive index	1.52	1.52
First aspheric constant A_1[a]	0.0099	0.00659
Second aspheric constant A_2[a]	−0.635	−0.0331
Primary mirror		
Spacing from front of corrector (m)	0.423	0.496
Diameter (m)	0.203	0.264
Curvature (1/m)	1.232	1.047
Secondary mirror		
Spacing from front of corrector (m)	0.011	0.0256
Diameter (m)	0.050	0.095
Curvature (1/m)	5.464	3.213
Cassegrain focus		
Spacing from front of corrector (m)	0.577	0.646
Rms blur at best focus[b] (m)	5×10^{-6}	1×10^{-6}
Magnification	1.46	1.25

[a]Surface contour of corrector plate front surface,
$z(r) = z_0 + A_1 r^2 + A_2 r^4$ (r is in meters).
[b]Based on 100 monochromatic rays traced randomly through the system.

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Collectors are positioned as needed to collect both colors of Doppler shifted light and direct them into a multimode fiber, which conveys them to a photodetector array. A dichroic mirror and multilayered dielectric optical filters are used to chromatically separate the collected light and direct it into four photomultiplier tubes, which then convert the optical signals into electronic signals. It should also be mentioned that this design relies on scattering angle for separation of the horizontal and vertical axis collected light, since both green and blue are used on each channel. For small scattering particles the scattering lobe at 90 degrees is quite small, so a collector oriented at slightly off-axis back- or forward scatter should receive little cross talk from the orthogonal probe volume. However, this situation changes in a very complex way for larger particles. Care must be taken to use small enough seeding particles that the noise contribution from side scatter is not significant. The level of side-scatter noise may be checked with the signal processor by blocking the laser beams on the backscatter axis and looking only at side-scattered light.

A technique for further increasing the collection solid angle involves clustering two or more collectors together so that they image nearly the same region of the probe volume and channeling their collected light into the same photodetector. The easiest approach involves launching the light from each collector into a multimode fiber optic placed just behind the spatial filter and orienting the output ends of these fibers to illuminate a single photodetector. Optical path length matching in the fibers is not critical because of the relatively long period of the Doppler signal (with respect to fiber transit times).

Translation Apparatus

The fixed focus design chosen for this instrument requires that the entire rigid frame be translated throughout the test section volume of interest. This requires a three-component linear traverse mechanism capable of moving the system quickly and accurately over a large distance. The design chosen for this instrument incorporates cylindrical case-hardened linear bearings and lead screws of the recirculating ball type. Stepping motors with digital controllers and optical-encoder feedback are used to control the motion of the frame. The frame is counter-balanced to reduce the load on the motors. The range of motion is ±18 inches from tunnel centerline in the vertical and cross-stream directions and 23 inches upstream or 77 inches downstream from the turntable centerline. The theoretical positioning reapeatability for the rig is 0.001 inch, based on encoder resolution and lead screw pitch. Various mechanical hysteresis and tolerance limitations of the bearings and ball screw degrade this

theoretical limit, particularly over long displacement. The position accuracy over the full range of travel is on the order of 0.010 to 0.050 inch, due to errors in the linear bearing mountings and other effects such as refraction of the laser beams by striae in the test section windows.

Signal Processing Electronics

Signal processing to determine the Doppler frequency is accomplished using Macrodyne time domain burst counter processors (ref. 6) and a Macrodyne (LVABI) autocorrelating digital buffer interface connected to a host MS-DOS PC/386 based computer. The system has the capability of processing up to four photomultiplier signals using four RF mixers and four RF downmix signal generators (IEEE-488 controlled). The custom-built 16-bit parallel interface (LVABI) allows simultaneous sampling of data in all desired channels. The system is located on the mezzanine side of the 7- by 10-Foot Wind Tunnel No. 1.

Signal Flow Block Diagram

Figure 4 identifies the signal flow through the system with an example of input, shifted, downmixed, and output values. Input scattered light signals from each of the three component channels are fed to respective photomultiplier tubes (PMTs) and given a 50-dB preamplifier boost. Each signal then passes to an individual TSI LV Frequency Shifter and mixes with a downmix signal from the HP Programmable Signal Source. The output frequency from the mixer is the difference of the two input frequencies; the original signal minus the downmix signal (e.g., input 40 MHz + 2 MHz shift – 37 MHz downmix = 5 MHz output). This mixing process reduces the bias caused by the 40-MHz Bragg Cell shift and permits the use of a narrower bandpass filter. The signal generators are controlled manually or by computer through IEEE interface. All signal channels are fed to an individual Macrodyne simultaneous burst detection processor where the S/N is maximized using high- and low-pass filter settings of 2 MHz and 8 MHz, respectively.

Signals are monitored using both an oscilloscope and RF spectrum analyzer. The data are then passed to the Macrodyne LVABI where the filtered bursts are stored until a predetermined number of samples, usually 500 to 1,000, are obtained. The three components of velocity are measured using either forward- or backscattered light. For all channels using the 514-nm line of the laser output, a simultaneous data acquisition feature of the LVABI was used to ensure burst arrival overlap of at least 80 percent. The coincidence feature of the LVABI was not used for the 488-nm channel, since the weakness of this signal

caused timing problems in the data acquisition computer. The filtered data are then passed to the PC/386 DAS system software in arrays for further calculations, storage, and graphical display.

Instrumentation Required

The following is a list of hardware components of the 3D LV system.

Instrument	Manufacturer/model
Tracking generator/ counter	Hewlett Packard 8443A
Spectrum analyzer– RF section	Hewlett Packard 8553B
Spectrum analyzer– F section	Hewlett Packard 8552B
Display section	Hewlett Packard 141T
Oscilloscope	Hewlett Packard 7663
Dual trace amplifier	Hewlett Packard 7A26
Differential amplifier	Hewlett Packard 7A22
Dual time base	Hewlett Packard 7B53A
Programmable signal source	Hewlett Packard 8165A
Photomultiplier tubes	Thorn EMI 9902B
PMT voltage supply	Avantek UAA-1132B
LV frequency shifter	TSI 9186A
LV frequency shifters	TSI 9186B
FED module	Macrodyne 2096-2
LOD module	Macrodyne 2096-3
FED module	Macrodyne 3001
LOD module	Macrodyne 3002
LVABI	Macrodyne LVABI
Motor controller	Shaw LM-HPIB
Stepping motor	Superior Electric M112-FJ112E
Encoder	Renco 25LE-100-8D3X2-C1-1

Data Acquisition and Control

The data acquisition system consisted of a Compaq 386-25 MHz based microcomputer with the following hardware and software components.

Hardware

Compaq 386-25 MHz personal computer

112 MB hard disk

45 MB Syquest removable hard disk

10 MB memory

Logitech track ball

NEC Multisync 2A super VGA monitor and card

Serial/parallel port connection

HP Deskjet 500

Software

National Instruments IEEE 488 GPIB-IIA card

National Instruments IEEE AT-DIO-32F card

GPIB-PC IEEE 488 Software Rev C.10

DOS Lab Driver Software 4.0 for AT-DIO-32F card

LV DRIVE Software 10/11/91 for Macrodyne LVABI

Grafmatic Software 4/5 MS FORTRAN for HISTOGRAM program

MS-DOS 5.0

MS FORTRAN 5.0

MS QuickBASIC 4.5

LV3D9QB.EXE (main program executable)

HISTOGRAM.EXE (graphics program executable)

Data Acquisition System Software

A stand-alone executable program (LV3D9QB.EXE) has been created by combining two high-level programming languages and device driver software. FORTRAN and QuickBASIC are the programming languages used, and DOS LabDriver, MS DOS Handler, LVDRIVE, and Grafmatic are the device driver software. The main body of the program is constructed in FORTRAN. Some subprograms are created in QuickBASIC since their device drivers only supported this option. Because of this limitation, it is necessary to combine these programming languages in what is known as "Mixed Language Programming." Since both languages are manufactured by Microsoft Corporation, this is possible. However, this

mode of operation is not directly supported. Additionally, it is necessary to make QuickBASIC the primary startup shell, from which FORTRAN or additional QuickBASIC subroutines can be called. The source code has been created for each section of the program, compiled, and linked with the appropriate options to create a stand-alone executable program. Individual routines (DAS, TRAVERSE, and GRAPHICS) have been developed to run as stand-alone programs for testing various system components. A detailed description for creating each part of the program is documented in reference 7 along with source code file specifications, appropriate testing programs, and reference materials.

Program Block Diagram

The program algorithm for all functions of the LV system is described in reference 8. This software includes the routines required for program initialization, data acquisition, and data postprocessing. Figure 5 shows the program control block diagram. Descriptive information on the main software module functions is given in the following paragraphs.

The three main computer subroutines are DAS, TRAVERSE, and GRAPHICS. Within these subroutines, a measurement cycle consisting of a sequence of events for acquiring, processing, and displaying the results is executed. "Points" are defined as averaged values that have been calculated from a large number of LV data samples. "Runs" are defined as a sequence of measurement locations along a predetermined path consisting of several points.

Subroutine: DAS

The data acquisition subroutine is responsible for initializing the LV system by controlling the hardware and software settings prior to each set of runs. The software allows the user to edit a series of menu options for all variable inputs. Once the necessary information is entered into the program, the system is in standby mode for data acquisition.

Subroutine: TRAVERSE

The traverse subroutine controls positioning, including the initialization of data registers, and display of current position and traverse units. Based on a user defined initial position, final position, and traverse increment, the traverse locations are computed.

Subroutine: GRAPHICS

The primary objective of this routine is to graphically display a histogram history for the three components of velocity. These plots are displayed as number of samples versus frequency for each channel. Both standard deviations and mean values are calculated for each velocity component and displayed next to each plot. The software provides the user with menu choices for data manipulation by eliminating spurious data points within certain specifications, changing the bin size, or changing the desired frequency bands. The final result of the graphics routine is an archived summary of all data point mean frequencies and velocities.

Software Verification

To verify the system software, a simulated signal was used for both hardware and software interfaces which allowed for data acquisition and analysis. Most of the system components were tested in the laboratory prior to actual wind tunnel testing to minimize the amount of troubleshooting involved. To simulate a test, the following hardware and software items are required.

1. Laser and (TSI 2D LV component system) optic assembly

2. Seeding (cool mistifier or vapor condensator)

3. Motor controller, stepping motor, and encoder

4. Signal processing equipment

5. DAS system (PC/386 computer)

6. DAS software (LVD9QB.EXE)

One way to test program operations is to simulate a downmix signal and burst signal using the HP Programmable Signal Generators. After connecting the instruments in this manner and running the executable program, a simulated signal can be analyzed along with movement of a single axis stepping motor. The input frequency from the signal generators for both burst and frequency units is observed as output from the program both computationally and graphically through the HISTOGRAM program. This is done primarily as a resolution check for the system. The significance of the output signal depends on parameters from the initialization file where variables such as filter band pass settings, fringe spacing, and traverse information are addressed. Data files are saved and imported manually into the graphics routine HISTOGRAM, usually after a series of runs. Integration of the graphics routine with the main program module has been accomplished, providing near real-time histogram viewing between acquired points.

Spinning Wheel Calibration

The fringe spacing is a function of beam pair convergence angle and laser wavelength and is given by the relation:

$$Dx = l/(2 \sin f)$$

where Dx is the fringe spacing, l is the laser wavelength, and f is the convergence half angle. The relationship between particle velocity normal to the fringe system and Doppler frequency is determined by the fringe spacing. Although the laser wavelength is precisely known, the beam pair convergence half angle is quite sensitive to measurement error.

A spinning wheel calibration method (ref. 9) has been devised at NASA Ames Research Center to determine the factors which convert the counter-processor measurements of frequency (MHz) to velocity (m/sec). The apparatus features 5-micron light scattering wires rotating at a known tangential velocity at the rim of the wheel. The focus point of the probe volume is directed through a small pinhole centered on the rotating disk and impinges on a solar cell connected to an analog voltage meter. The probe volume is first centered on the pinhole by maximizing the voltage meter output. The disk is then translated to place the probe volume at a precisely known radial position where scattering from the wire filaments provides a strong calibration signal. An external inhibit is needed to disable data acquisition while the six disc spokes that support the outer rim on the wheel pass through the probe volume.

Since the laser beam components are weakly coupled, multivector techniques developed for strongly coupled (nonorthogonal) systems (ref. 10) are not required. Other calibration techniques require making detailed measurements of the laser beam geometry to analytically determine the exact calibration constants. The method used with this system is simply to measure the Doppler frequency of scattered light detected when the component fringe system moves perpendicular to the rim of the wheel. The ratio of this Doppler frequency to the tangential velocity determines the sensitivity or calibration coefficient determined for the specific component channel. This information is entered into the initialization file and used to compute velocity components.

Experimental Testing

This instrument has been developed in response to specific testing requirements and has been used in two wind tunnel tests. Sample results are presented here to provide an indication of system capability. The tests are described as follows:

An Experimental Study of the Flow Field Surrounding a Subsonic Jet in a Cross Flow (ref. 11)

This test provided measurements of the surface pressure patterns and flow field velocities created by the interaction of a round subsonic jet exhausting perpendicularly from a flat plate in a subsonic cross flow. The motivation behind this was to assist in the evaluation of computational fluid dynamics (CFD) codes applied to this type of interaction. This test was part of a combined experimental/CFD program at NASA Ames Research Center to validate computational methods for complex jet flows by building a detailed data base. Figures 6 and 7, adapted from reference 11, are included to illustrate the utility of the instrument in the documentation of this complex flow field.

Experimental Investigation of Spanwise Blowing on a 40 Degrees Swept Trapezoidal Wing (ref. 12)

This test investigated the effects of spanwise blowing using the jet assembly previously cited in conjunction with a moderately swept trapezoidal wing set at an angle of attack of 20 degrees. It is known that the flow over a thin highly swept wing at moderate to high angles of attack separates at the leading edge and produces a stable vortex over the wing with large vortex-lift increments. However, for moderately swept wings, vortex breakdown occurs at lower angles of attack, thus reducing the vortex-lift increment. The purpose of this test was to minimize vortex breakdown and maximize vortex-lift increments through spanwise blowing. Additionally, various flow visualization methods such as pressure sensitive paint, schlieren optics, and surface oil flow visualization were used to qualitatively analyze the behavior of the flow about the wing. A panel code method, PMARC, was also evaluated by comparison with the experimentally obtained results for various cases. Figures 8 and 9, adapted from reference 12, are included to illustrate the utility of the instrument in the documentation of this complex flow field.

During the course of these investigations, two important records were generated by the program control software. The first record was the initialization file as seen in figure 10. This file allowed the user to customize the system settings prior to each set of runs. Information such as traverse coordinates, LVABI active channels, coincident channels, fringe spacings, and downmix directions were modified as needed prior to each run. This file provides a permanent record of the instrument setup and operating parameters. During the course of a run, the only changes made were generally those involving the traverse system parameters.

The second record was the histogram display seen in figure 11. It graphically displayed the velocity distribution for all active channels. Initially the graphics routine was not an integral part of the program software. Postprocessing of the raw data was required to obtain the velocity histograms. The graphics routine has since been integrated within the main program to provide near real-time velocity histogram displays. Mean and standard deviation of velocity for the corresponding channels are displayed as well. The program also allows the user to adjust the number of histogram bins and to cull spurious data. Reference 12 contains more detailed information on the HISTOGRAM program.

Error Analysis

Experimental measurement systems must be evaluated to determine the precision and accuracy of the measurements provided. This is an essential step in the experimental process and establishes confidence in the measurements for their intended application. For LV systems, this process may become quite complex in view of the wide range of statistical bias sources (ref. 13). Ideally, a known metric standard with statistical characteristics similar to the subject flow field should be measured and systematic comparisons made. Another approach is to use redundant instrumentation and make comparisons. However, it may be difficult to assign a measurement disparity to one instrumentation system or the other. As a minimum, the LV system should be calibrated at the beginning and end of the test program to verify the integrity of the system sensitivities over the duration of the test.

Unfortunately, time and program cost constraints did not permit a systematic error analysis for either of the tests cited in references 7 and 10. The accuracy and precision for this system have not been thoroughly quantified. Some quantitative information for the calibration techniques is available and is discussed. Additional discussion is included to identify possible error sources and their potential impact on system performance.

Calibration Error

The spinning disk calibration device is subject to uncertainty in the rotational speed, radius, and angle values whose products are the calibration velocity vectors. The speed of the synchronous electric motor is determined by the AC line frequency. The utility specifies 60 ± 0.02 Hz as a standard for the AC transmission lines. This frequency error translates directly to angular velocity error. The radial position at which the wires pass through the probe volume is measured with a vernier scale with precision of 0.002 inch (50 microns). The probe volume

must first be centered on a predrilled hole along the shaft axis with a solar cell transducer connected to an analog voltmeter. The ability to center the probe volume on the disk is a function of probe volume diameter. For the nominally 300-micron probe volumes of this system the precision of this adjustment is conservatively estimated at 100 microns, providing a total uncertainty in radius of 150 microns at a nominal radius of 2 inches (50.8 mm).

The angular measurement capability for the wheel relies on proper zero adjustment using back reflections from the wheel surface, and measurements from a vernier scale for setting a specified angle for the velocity vector. These measurement errors are on the same order as for the radius measurement. However, for the direct calibration method used in the test programs cited, these errors in angle cause errors in measured velocity that are proportional to only the sine of the angle error. Therefore, for the calibration technique used here, angular errors are negligible. Therefore, the frequency and radius uncertainty combine to cause a 0.3 percent uncertainty in the calibration velocity vector magnitude of 19.15 m/sec. This is a bias error for the measurement system if only a single calibration is done. The bias error may be reduced with multiple calibrations.

Filter Bandwidth

As mentioned earlier, the photomultiplier signal output is band-pass filtered (2 MHz to 8 MHz) to improve the quality of the waveform entering the counter processor. The fringe spacing for this instrument provides a corresponding velocity bandwidth of about 100 m/sec. Automated downmixing ensures that the mean velocity will be centered within this bandwidth. However, for extremely turbulent flows (such as an unstable vortex) some outlying turbulent data may be attenuated by the filters. For a bimodal flow, such clipping may affect both the mean and turbulence intensity measurements. For random turbulence, the mean should not be appreciably affected but the measured turbulence intensity will be less than actual. It is possible to open up the band-pass range and change the downmix center frequency if the operator is cognizant of the presence of high turbulence levels.

Optical Noise from Wall and Surface Reflections

Sometimes it is necessary to measure close to a wall or model surface. In these regions, intense diffuse reflections from the surface (with zero Doppler shift) will overpower the signal. Where feasible, special cover glass slides with a dielectric coating have been used to minimize these reflections and allow closer surface measurements. These slides are coated for very high reflection of the argon-ion

laser wavelength band. This effect is further reduced by the efficient spatial filtering inherent to the collector design.

Test Section Window Effects and Beam Overlap

The 7- by 10-Foot Wind Tunnel No. 1 test section has three 4-foot by 6-foot by 1/2-inch thick framed window panes of commercial window glass on both test section sides and ceiling. Beams which transmit through the glass are refracted. Since the glass surfaces are not optically flat, the beams refract by varying amounts as the instrument is translated over the window aperture. This causes some loss of beam overlap, reducing or effectively eliminating the Doppler signal. No particular solution to this problem has been developed other than marking and avoiding regions of the glass that have poor surface flatness and keeping the probe volume large enough to maintain some overlap with expected levels of refraction.

Seeding

Particle size distribution and density have a critical effect on signal quality. Particles must be small enough to track the flow turbulence yet large enough to scatter sufficient light. It is generally desirable to have a single particle in the probe volume at a time, as well as a very narrow particle size distribution centered on an optimum size that is matched to the optical characteristics of the instrument. In the test programs cited, particle sizes on the order of 5 microns were generated using a Rosco vaporization/ condensation smoke unit and fogging compound and resulted in typical single channel data rate of 500 samples/second. No particle size measuring scheme was used other than the given manufacturer specifications for the particle generating fluid.

Concluding Remarks

This paper has described an LV instrument that has been designed, fabricated, installed, and implemented in the 7- by 10-Foot Wind Tunnel No. 1 at NASA Ames Research Center. The instrument is based on a three-component fixed focus design. A rigid, lightweight frame mounted to a translation apparatus surrounds the tunnel on both sides and the top. The laser, color separation, beamsplitter, Bragg cell, and beam focusing optics are all mounted in the top of the rigid frame. Modular Schmidt–Cassegrain collectors may be positioned anywhere on the frame to provide forward-, side-, or backscatter signal light collection. Multimode fibers are used to transmit the optical signal to remotely located photomultiplier tubes.

Commercial counter processors are used to process the Doppler signal. A three channel simultaneity interface may be used to ensure that Doppler bursts are coincident within a narrow time window. Software controlled downmixing of the Doppler signal is used to shift the signal frequency to be centered in a relatively narrow bandpass filter. Customized software for traverse motion control, data acquisition and processing, and graphical display have been described.

The instrument has been implemented in two wind tunnel test programs. Results from these studies have been discussed with attention to the capabilities of the instrument. A discussion of the sources of measurement error has also been presented.

Future Plans

Recent advances in the area of frequency domain processing will be incorporated into this instrument in the future. Modern commercial frequency domain processors are capable of extracting the Doppler signal from a very noisy signal. These processors will enhance the instrument's ability to operate close to model surfaces as well as alleviate the effects of other signal-degrading mechanisms as discussed previously.

Additional work with error analysis for the system is also required. Future test programs will provide the opportunity to evaluate calibration drift, measurement repeatability, and comparison with redundant measurements.

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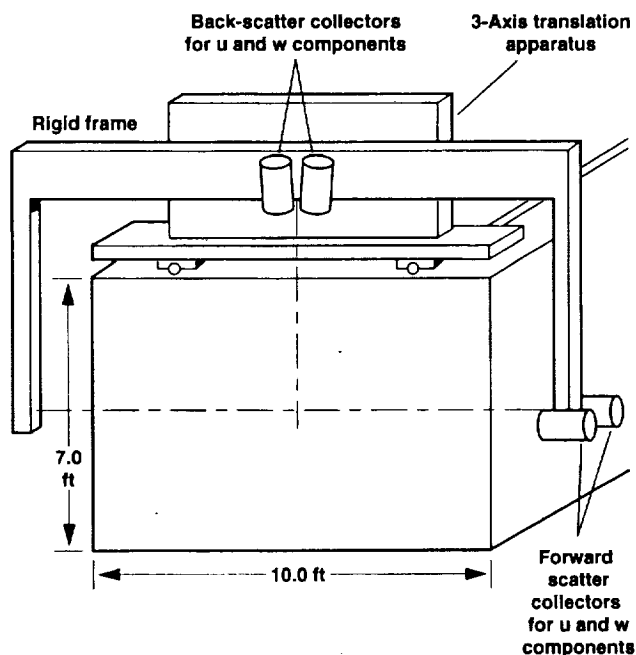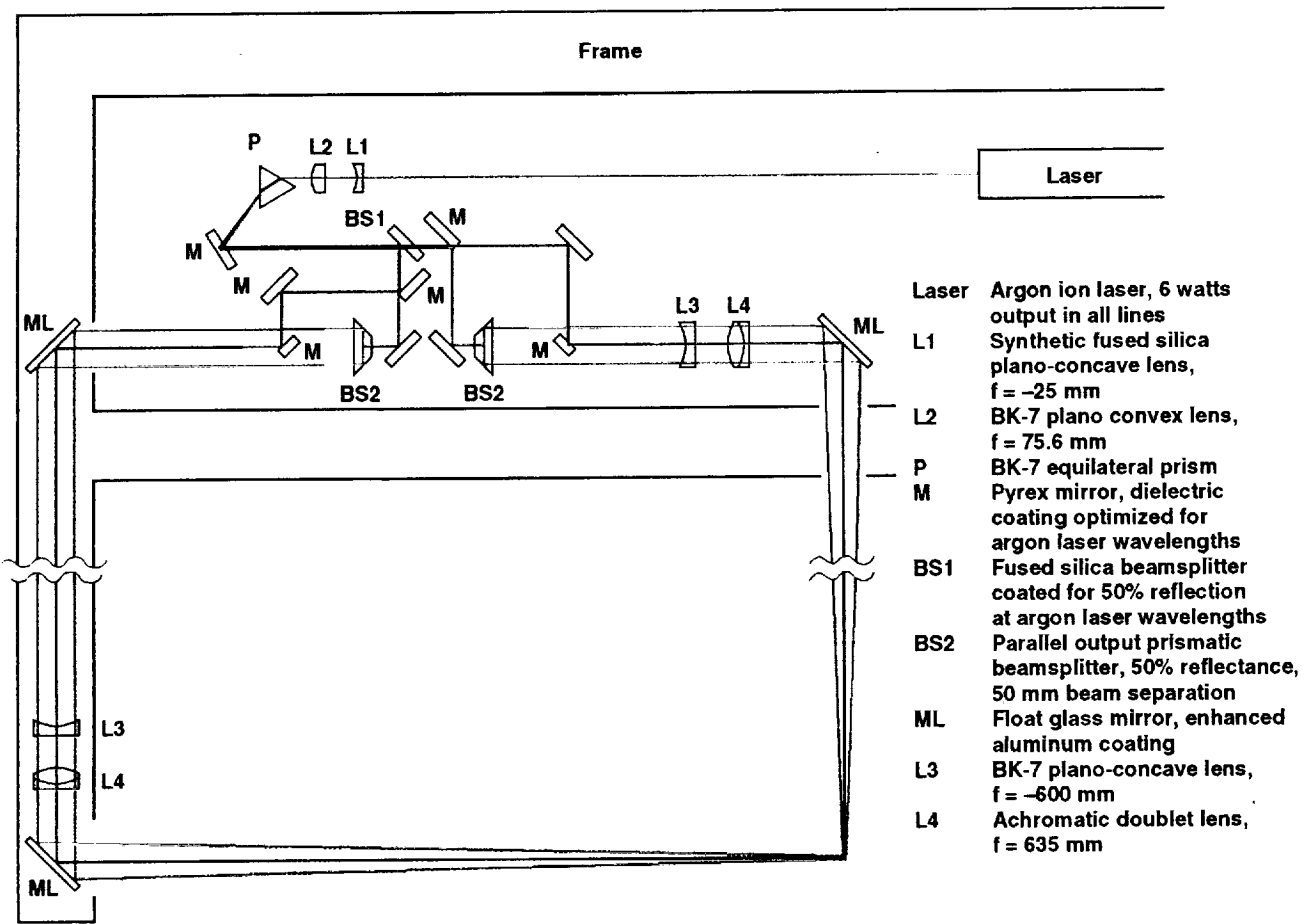
Figure 1. Instrument components.

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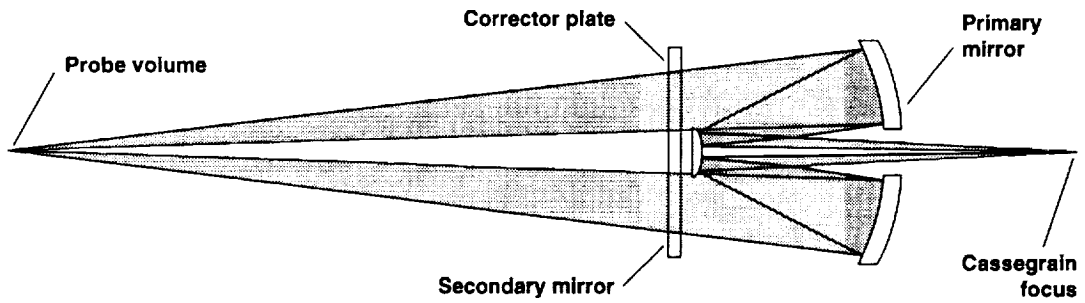Figure 2. Optical layout for laser beam manipulation.
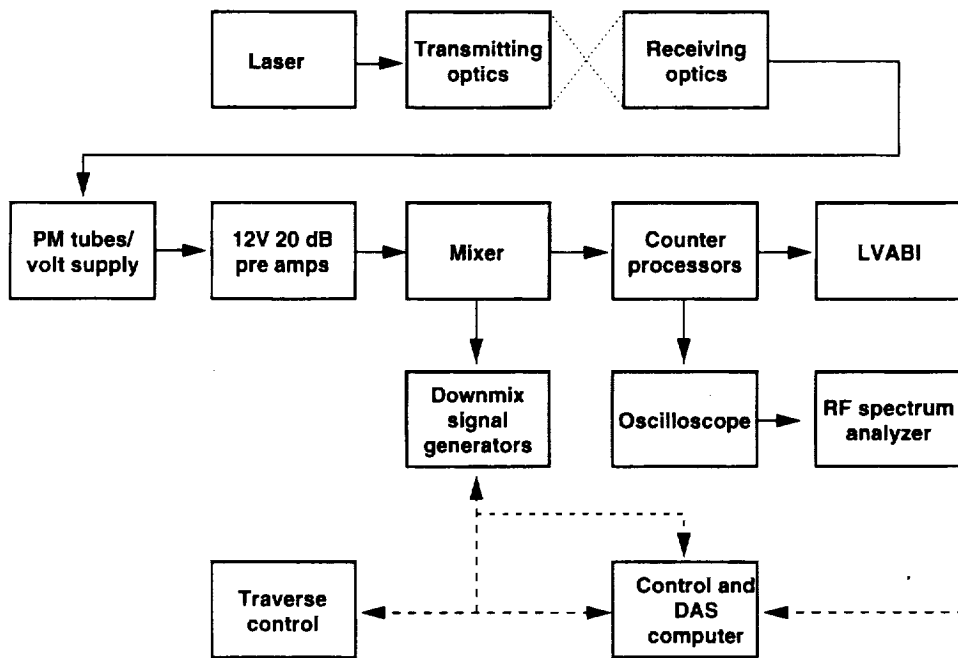
Figure 3. Modified Schmidt–Cassegrain light collector.

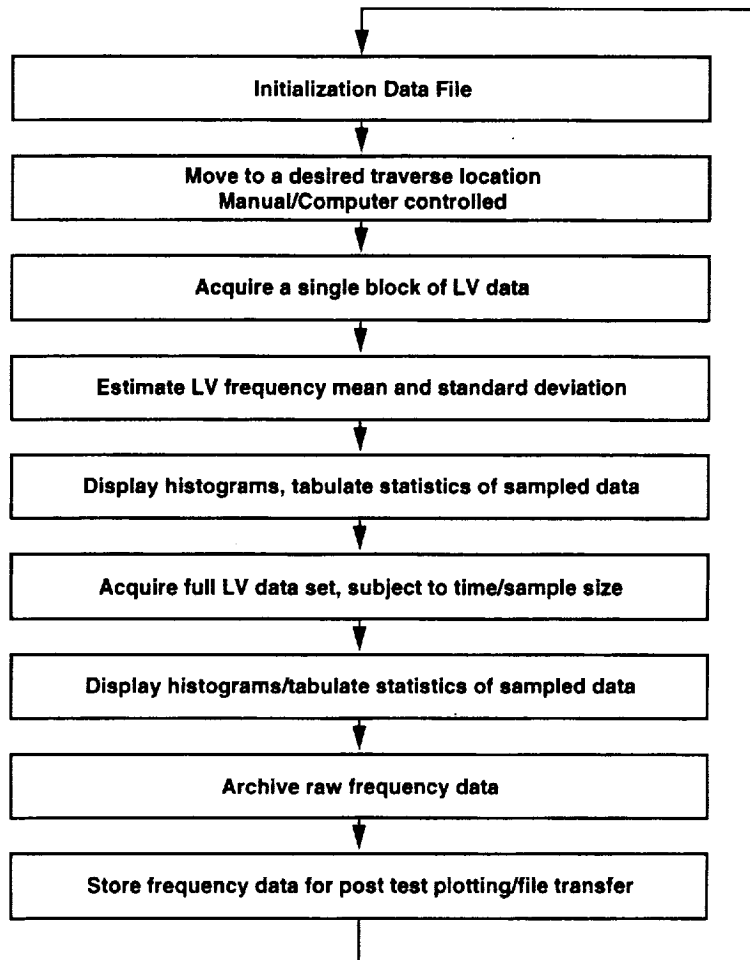Figure 4. Signal processing system block diagram.
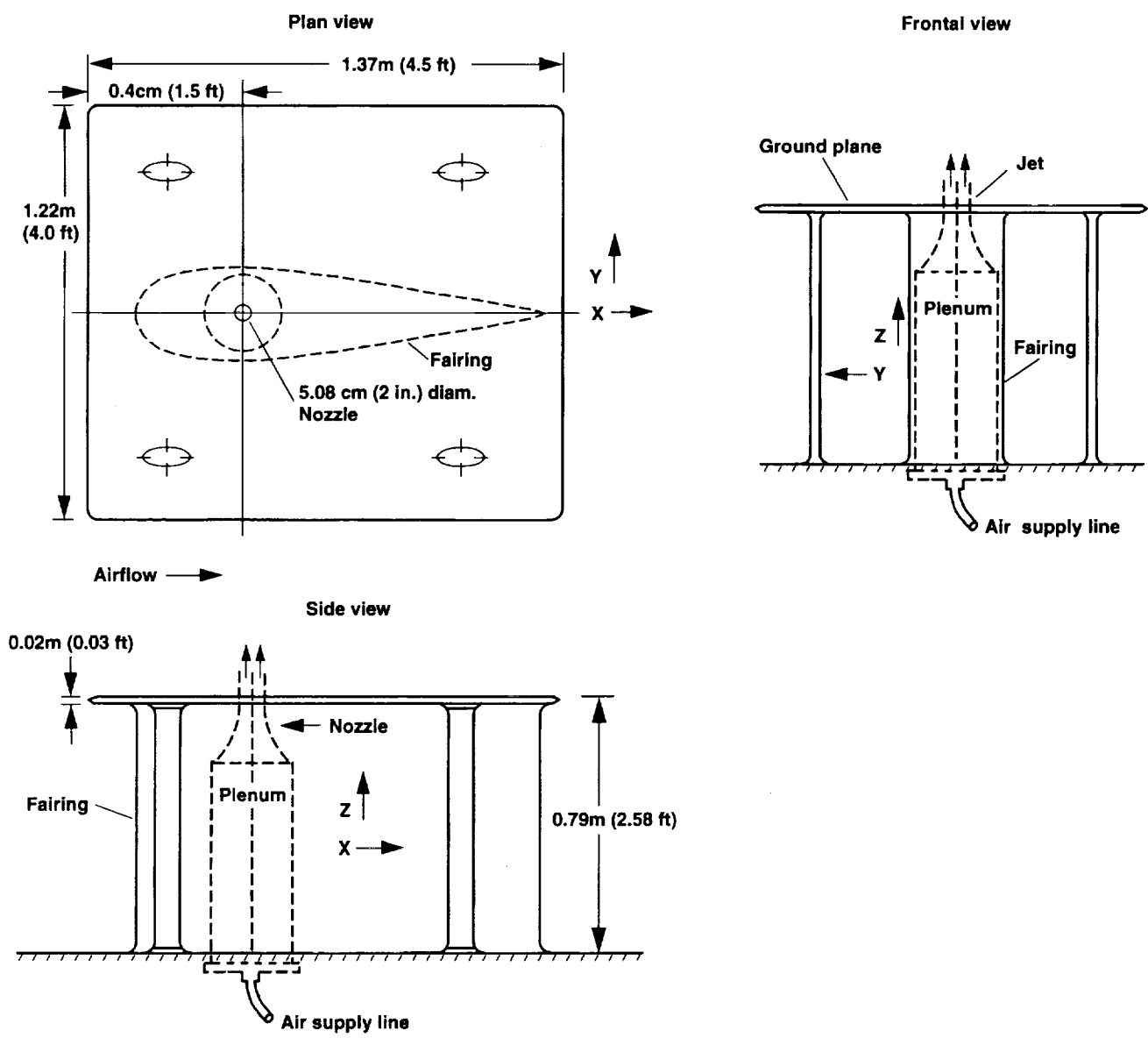
Figure 5. Software block diagram.

Plan view

1.37m (4.5 ft)

0.4cm (1.5 ft)

1.22m
(4.0 ft)

Y

X

Fairing

5.08 cm (2 in.) diam.
Nozzle

Airflow

Frontal view

Ground plane

Jet

Z

Plenum

Y

Fairing

Air supply line

Side view

0.02m (0.03 ft)

Nozzle

Fairing

Plenum

Z

X

0.79m (2.58 ft)

Air supply line

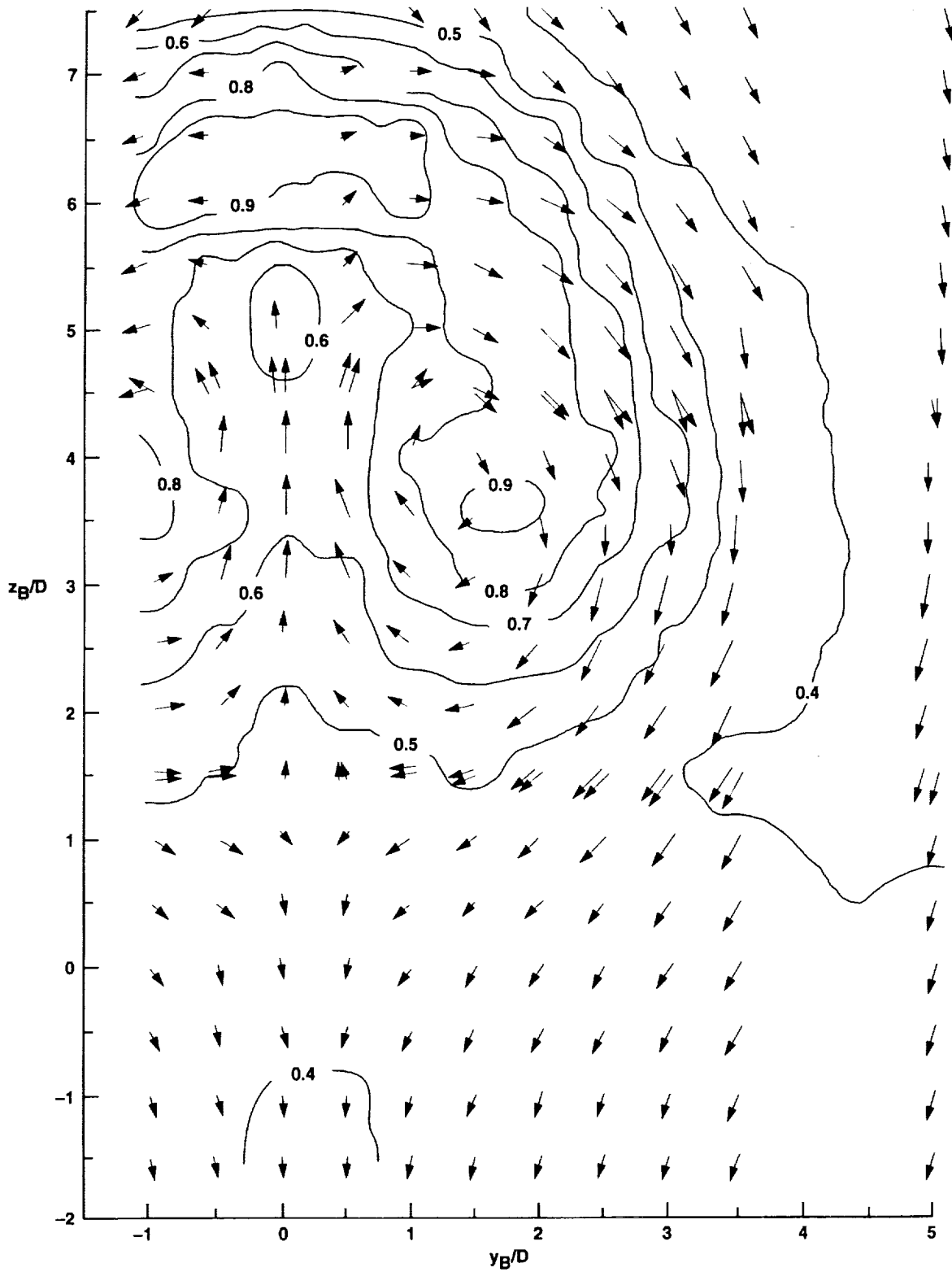*Figure 6. Experimental setup for jet in cross-flow experiment.*

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Figure 7. Measured in-plane velocity vectors and vorticity contours for a jet in cross flow.
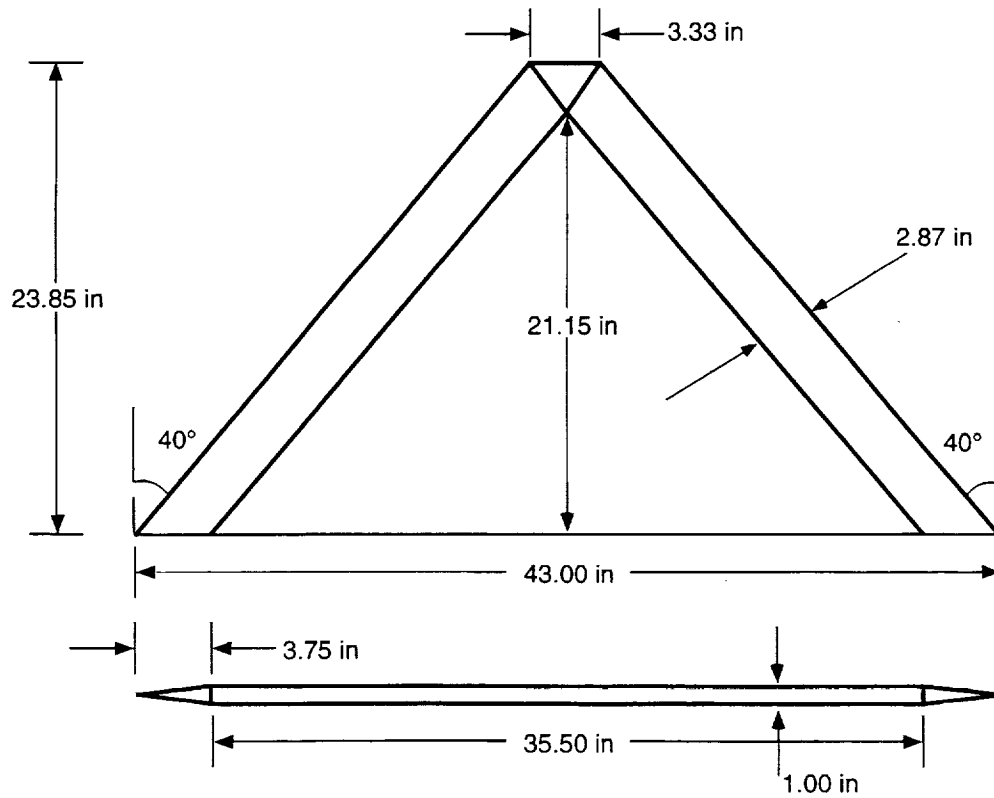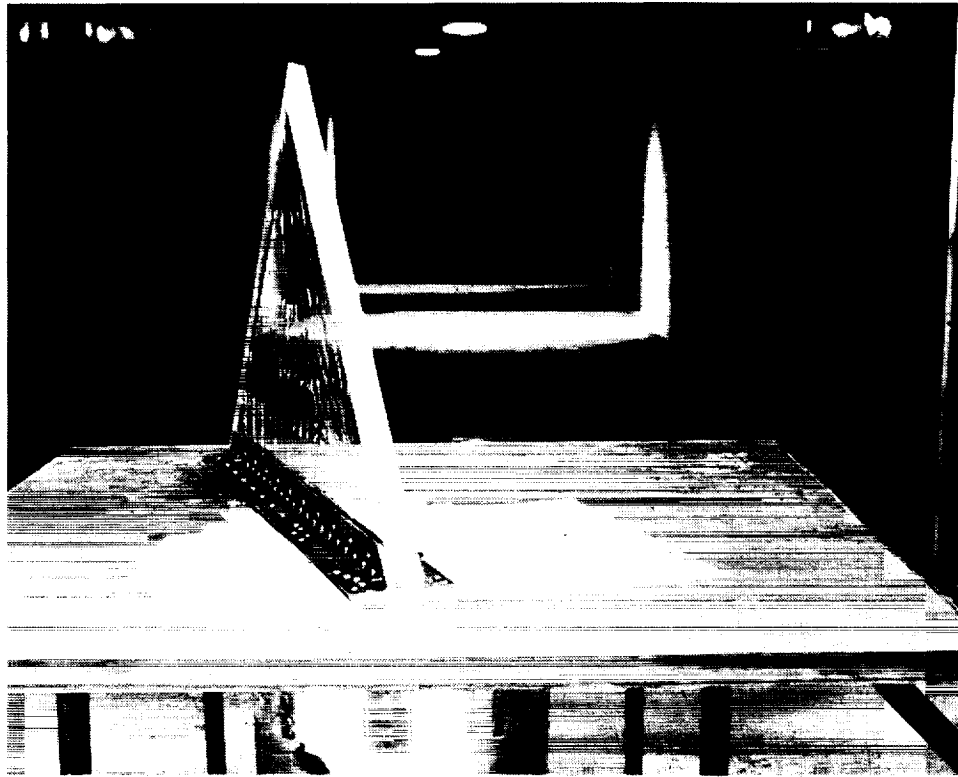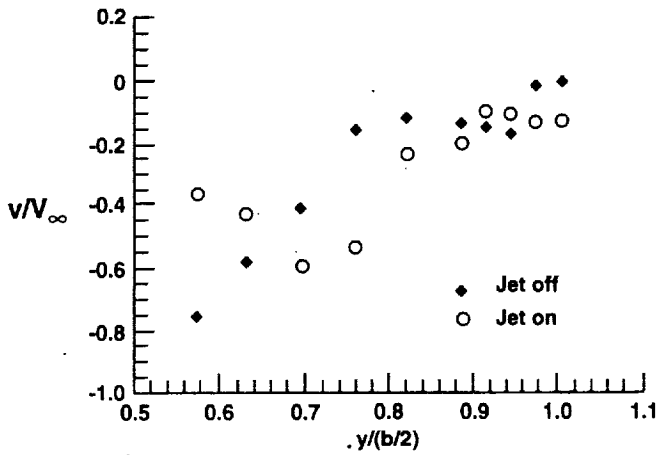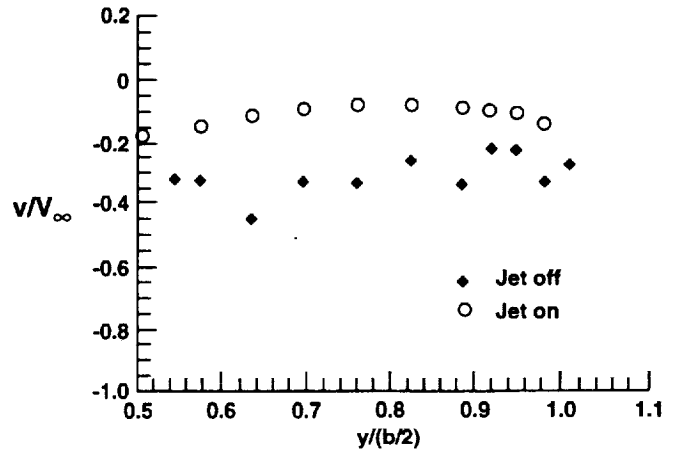
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Figure 8. Experimental setup for spanwise blowing experiment.

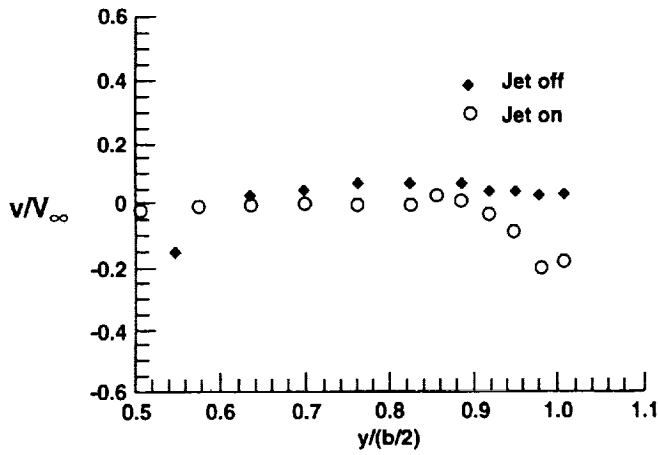**(a) Traverse taken 0.5" behind trailing edge 1.0" below wing's center line**

(b) Traverse taken 0.5" behind trailing edge, 0.5" below wing's center line

(c) Traverse taken 0.5" behind trailing edge, 0.5" above wing's center line

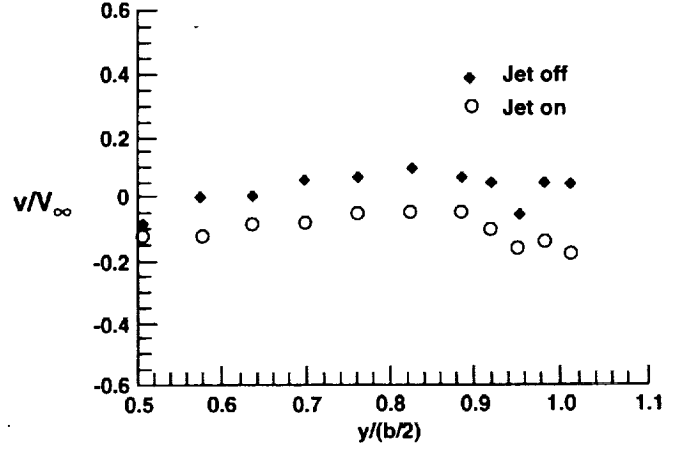**(d) Traverse taken 0.5" behind trailing edge, 1.0" above wing's center line**

Figure 9. Measured velocity profiles from spanwise blowing experiment.

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```
                    LV Initialization File: INITDB.DAT
                              Test 746


 1.  Run Number: 100
 2.  Date: 4/29/92
 3.  Mode: 2 -
 4.  Remarks:
        Jet survey:  Jet Off                                      2
           Wind Tunnel Testing With Plexiglas Wing On             2
           Traverse Along T.E. of Wing                            2
           Tunnel q = 10.3 lbf/ft²                                2
        Tunnel seeding on - smoke                                 2
        Jet seeding on - mineral oil                              2
 5.  Traverse operation (automatic or manual):  Automatic
        a.  Traverse units (in or cm):  in
        b.  Traverse reference position (x, y, z):
              +000.000,   +000.000,   +004.000
        c.  Initial survey position (x, y, z):
              017.296,    +008.182,   +018.103
        d.  Final survey position (x, y, z):
              022.553,    +010.182,   +012.000
        e.  Traverse increment: 0.500
 6.  Active LVABI Channels (0, 2, 4, 6):                       1110*
 7.  Coincident Channels    (0, 2, 4, 6):                      0000*
 8.  Downmix IEEE-488 addresses: 0,                            701, 702*
 9.  Data Block Size (200, 500, or 1000):                      500
10.  Maximum time/data block (seconds):                        300
11.  Maximum time/location (seconds):                          900
12.  Maximum number of data blocks (<11):                      1
13.  Desired confidence in mean velocity, per channel (m/s): 0.2
14.  Frequency-to-velocity conversion factors (m/s MHz):
            18.829       0.000       0.000       0.000
            0.000        0.000      -19.708      0.000
            0.000       -17.638      0.000       0.000
            0.0          0.0         0.0         0.000
15.  Fringe spacing, per channel (microns):
            18.829      -19.708     -17.638
16.  Average frequency tolerance to reset downmix (bandwidth +/-): 0.10
17.  Sample rejection criteria (standard deviation +/-): 3.0
18.  Bandwidth tolerance: 4.000
19.  Downmix direction factors (+1.0 or -1.0): +1.0, +1.0, +1.0
20.  Bragg cell frequencies (40 or 0.0): 40
```
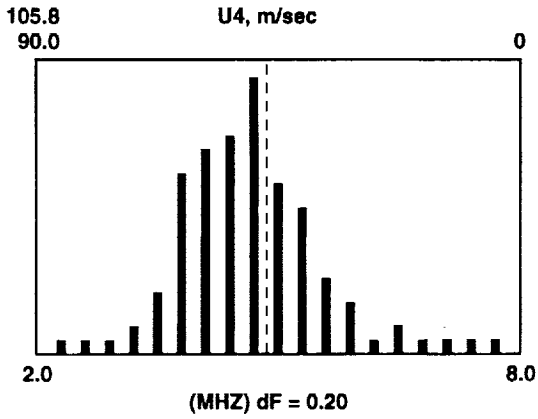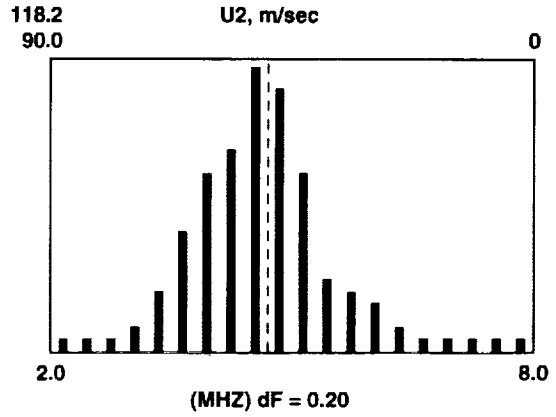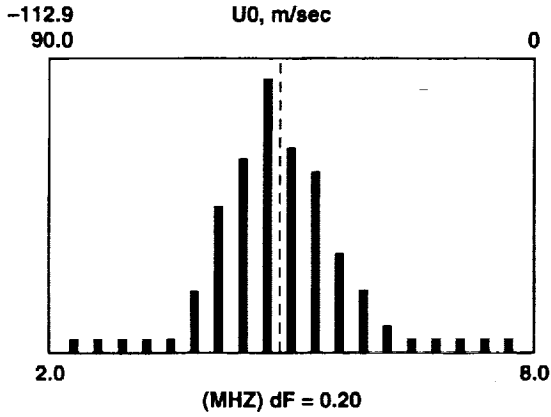
Figure 10. Sample initialization file for LV system software.

−112.9 **U0, m/sec**
90.0   **0**

2.0   **8.0**
(MHZ) dF = 0.20

118.2 **U2, m/sec**
90.0   **0**

2.0   **8.0**
(MHZ) dF = 0.20

105.8 **U4, m/sec**
90.0   **0**

2.0   **8.0**
(MHZ) dF = 0.20

LDV display information
Mean U0 4.301
Mean U2 4.670
Mean U4 4.028
STDV U0 0.550
STDV U2 0.591
STDV U4 0.522
Samples 500
Enter <CR> To exit display

Figure 11. Sample histogram generated with program HISTOGRAM.

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REPORT DOCUMENTATION PAGE

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A three-component dual-beam laser-velocimeter system has been designed, fabricated, and implemented in the 7- by 10-Foot Wind Tunnel at NASA Ames Research Center. The instrument utilizes optical access from both sides and the top of the test section, and is configured for uncoupled orthogonal measurement of the three Cartesian coordinates of velocity. Bragg cell optics are used to provide fringe velocity bias. Modular system design provides great flexibility in the location of sending and receiving optics to adapt to specific experimental requirements. Near-focus Schmidt–Cassegrain optic modules may be positioned for collection of forward or backward scattered light over a large solid angle, and may be clustered to further increase collection solid angle. Multimode fiber optics transmit collected light to the photomultiplier tubes for processing.

Counters are used to process the photomultiplier signals and transfer the processed data digitally via a buffered interface controller to the host MS-DOS computer. Considerable data reduction and graphical display programming permit on-line control of data acquisition and evaluation of the incoming data. This paper describes this system in detail and presents sample data illustrating the system capability.

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Wind tunnels, Laser Doppler velocimeters, Optical fibers

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