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About TSI

- Instrumentation to ensure safety, comfort and health of people and enhance productivity and quality
- Over 500 employees world wide, over $ 85 million in revenues
- Products include fluid mechanics and particle research instruments, industrial process control instruments, industrial test and environmental instruments, meteorological instruments

TSI was founded in 1961 as a manufacturer of Thermal Anemometer systems. Over the last 36 years we have grown to be a company with over 500 employees and over $ 85 million in annual revenues. TSI is committed to being the premier supplier of instrumentation for a variety of markets. TSI instruments are used worldwide to ensure safety, comfort and health of people and enhance productivity and quality. Among all the divisions of TSI, the Fluid Mechanics Instruments Division (FMID) is dedicated to supplying quality instrumentation to address the measurement needs of a fluid dynamic researcher. Other related products include Phase/Doppler Particle Analyzers for size characterization in sprays.

Some of the other TSI products include aerosol generators, instruments for detecting, sampling, conditioning and sizing air borne particles. Non-contact laser based length and velocity measurement systems are routinely used in hostile industrial environments as found in steel industry. Industrial test instruments such as respirator fit testers, portable air velocity meters, room pressure monitors and controls, gas sensors etc. are used to ensure safety in the work place. TSI through our subsidiary Handar also manufactures meteorological and hydrological instrumentation used in remote weather monitoring.

TSI is a stable, healthy company that stands behind its customers and its products.

Fluid Mechanics Instrument Division (FMID)

- Most experienced division - TSI started with thermal anemometry instruments
- Products include Laser Doppler Velocimeters, Thermal Anemometers and Particle Image Velocimeters and Phase Doppler Velocimeters
- Standard as well as custom systems for a variety of applications

The FMID division manufactures and markets fluid mechanics research instruments world-wide. Over the last 36 years hundreds of HWA, LDV and PIV instruments were installed worldwide. In addition to standard systems, FMID has designed several custom systems to address specific needs of the customer. Special systems range from Tow/Wave tank LDV systems, high temperature and cryogenic LDV systems to special hot wire/film probe designs. Our PIV design concept factors in a lot of flexibility to accommodate our users' varied requirements.

few of our accomplishments include:

First 200 MHz LDV signal processors

First computer controlled LDV signal processor

First signal processor with burst centering, automatic sampling rate adjustment

First SNR based Doppler Burst detector

First commercial co-axial 3 component LDV system

First diode based commercial LDV system

First commercial PIV system

First computer controlled thermal anemometer

First Constant temperature anemometer with automatic frequency response tuning

First commercial adaptive phase/Doppler velocimeter

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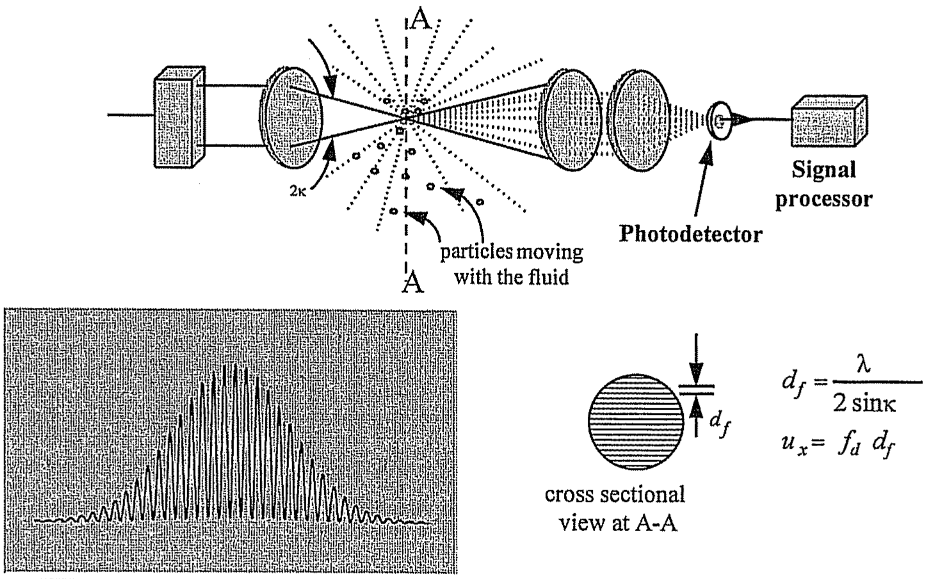
Laser Doppler Velocimetry

Dual beam approach

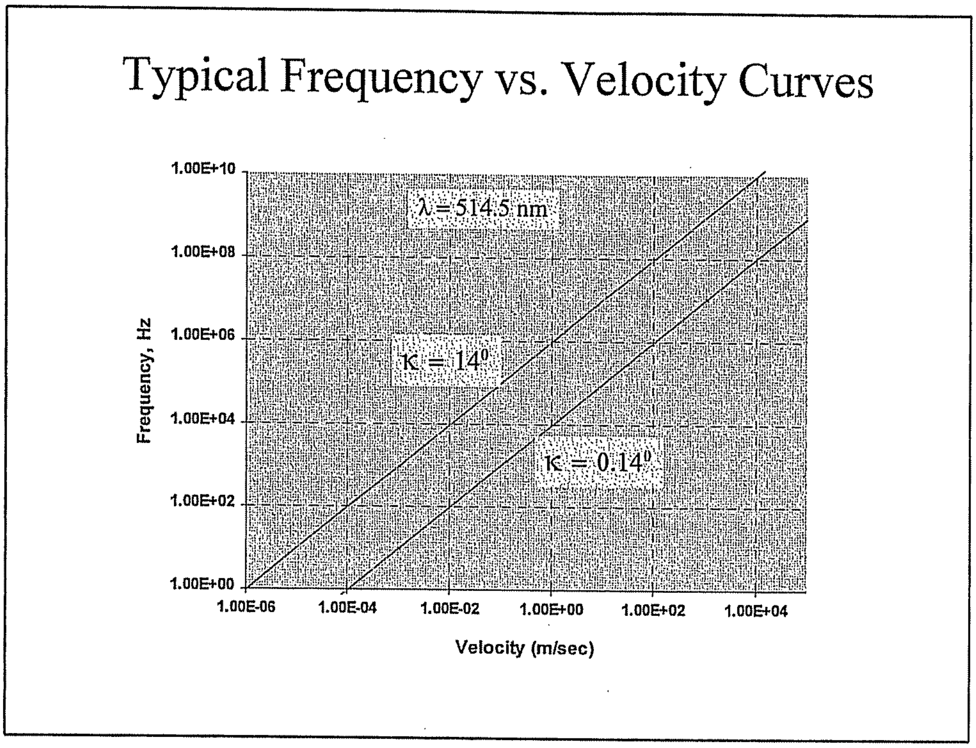


The dual-beam approach is the most common optical arrangement used for an LDV system. Basic components of a complete LDV system include a Laser (He-Ne, Argon-ion), Beamsplitter, Focusing lens, Collecting lens, Pin hole, Photodetector, Signal processor, Data Analysis system. To optimize a measurement, one must have: Particles that follow the flow and provide an adequate signal; Laser, optics and photodetector that provide an optimum signal-to-noise ratio at the photodetector output; a signal processor that extracts the maximum amount of information from the signal, data processing techniques that provide the needed flow properties from the output of the signal processor.

"Differential Doppler" is another term applied to the Dual-Beam technique. This correctly implies Doppler shifted scattered light signals are from a particle illuminated by two beams. This scattered light mixes at the photodetector surface to give the "difference" signal. The amplitude variation of the signal reflects the Gaussian intensity distribution across the laser beam.

Collection (receiving) optics for the dual beam system can be placed at any angle (forward/back scatter). The resulting signal from the receiving system will still give same frequency. However, signal quality and intensity will vary greatly.

The relationship between the velocity and the frequency of the photodetector signal is linear. d_f , the fringe spacing, is independent of the properties of the fluid medium.

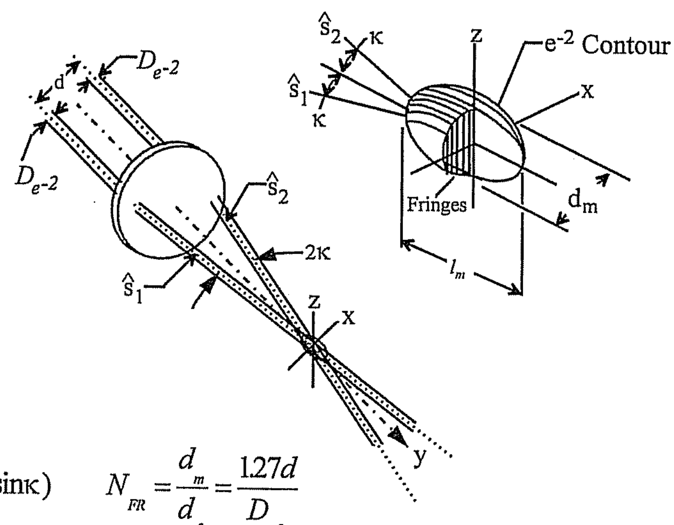


- Velocity dynamic range of over 10^8 is generally achieved by LDV systems
- For most common flows, the corresponding Doppler frequencies are in the MHz range.

The value of $\kappa = 14°$ represents a lens with an F-number (focal length/diameter) of 2. At $k = 0.14°$, the F-number would be about 200. These are reasonable limits using a single focusing lens even though $F^{\#}$'s of 1.2 are feasible—as any camera enthusiast can tell you. The absolute minimum fringe spacing, d_f, is the laser wavelength divided by 2 (i.e., when $\sin \kappa = 1$). This gives frequencies of about 4 MHz per m/s of velocity for visible wavelength lasers ($\lambda \cong 0.5$).

In practice, measurements from 1 μm/sec to over 1,000 m/sec have been made which corresponds to a dynamic range of over 10^9.

Measurement Volume Dimensions



$$d_{e^{-2}} = 4f\lambda / \pi D_{e^{-2}}$$

$$d_m = d_{e^{-2}} / \cos\kappa$$

$$l_m = d_{e^{-2}} / \sin\kappa$$

$$V = \pi d^3_{e^{-2}} / (6\cos^2\kappa \sin\kappa) \qquad N_{FR} = \frac{d_m}{d_f} = \frac{1.27d}{D_{e^{-2}}}$$

The volume is the ellipsoidal surface shown above, and it corresponds to the surface on which the amplitude of the fringes is $1/e^2$ of the maximum amplitude, which occurs at the center of the measurement volume. $D_{e^{-2}}$ is the diameter of the unfocused Gaussian laser beam measured at $1/e^2$ of the centerline intensity, and $d_{e^{-2}}$ is the corresponding diameter at the focal spot.

The choice of beam angle, κ, is restricted by the following considerations:

1) With single lens systems, ratio of f/d is related to the F# of the lens and 2 is a reasonable minimum. At low F#'s, particularly if $D_{e^{-2}}$ is large (expanded beam), lenses corrected for spherical aberrations must be used.

2) Frequency increases with increasing angle κ.

Seed Particles - Air and Water

Particles	Medium	Density (g/cc)	Refractive Index	Dia (μm)
Silicon Carbide	Air/Water	3.2	2.65	1.5
Nylon	Air/Water	1.14	1.53	4.0
PSL	Air	1.05	1.55-1.6	0.5
TiO2	Air/Water	4.2	2.6	3-5
Hollow glass beads (HGB)	Air	1.05-1.15	1.5	8-12
Metal coated HGB	Water	1.65	0.21 (R) 2.62 (I)	14
Peanut oil	Air	0.91	1.47	---

For air flows seeding is always necessary. For water in forward-scatter, naturally occurring particles will usually give a nearly continuous signal and follow the flow well but in back scatter seed material may be necessary.

For most measurements, the most desirable particle concentration is the highest possible while still keeping a low probability of more than one particle at a time in the measuring volume. Also, in the ideal case, all the particles in the flow should be large enough to give a good signal and small enough to follow the flow.

Seeding Techniques for Air:

- Disperse dry powders
- Generate liquid droplets
  - Start with solution- leaves solid particle of solute when dry
  - Start with mixture of high & low vapor pressure materials (e.g., oil and alcohol)
  - Disperse solid particles suspended in a liquid by drying droplets
- Evaporation and condensation of a liquid

It must be remembered that required particle motions are relative to the mean properties of the flowing stream (Lagrangian coordinates). In high-speed flow, for example, a stationary hot wire (Eulerian coordinates) might indicate frequencies up to 50 kHz. However, if one would move the probe with the mean flow so only relative motion was sensed, the frequencies might be much lower. This is the case with particles in the flow.

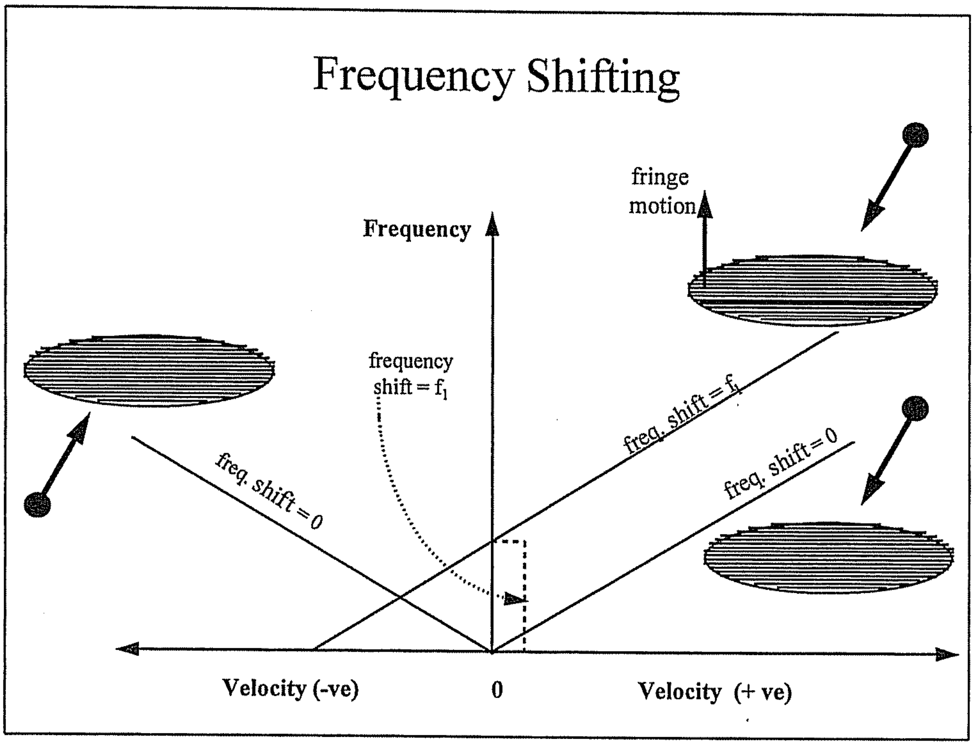
Frequency Shifting

Purpose:

1. To measure flow reversal.
2. Measure small component of velocity (in the presence of a large component).
3. Extend the range of low and high velocities that can be measured by a processor.

Frequency shifting is most often associated with the need to measure negative flows. It also provides the ability to measure a small component of a large total vector, "bring" the Doppler frequency within the range of the processor, etc. In addition, frequency shifting is used to measure flow velocities in highly turbulent flows.

Frequency shifters have also been used to separate the Doppler (velocity) signals in a multichannel LDV system using the frequency separation approach.



Doppler Frequency f_D = Velocity/Fringe Spacing

To resolve negative and positive velocity, frequency shifting is used.

Frequency F = SHIFT FREQUENCY ± |VELOCITY|/fringe spacing

The frequency value on the y-axis is the frequency of the signal input to the signal processor. Subtracting the shift frequency provides both the magnitude and direction of the flow.

In practice, a fixed 40 MHz shift is used by employing a Bragg cell. Depending on the magnitude of reverse flow this 40 MHz is down mixed to a value that is > twice the Doppler frequency corresponding to the negative velocity. This ensures that the flow direction is determined accurately, while maximizing the resolution of the velocity measurement. The direction of fringe motion is usually selected to be opposing the mean positive flow. This implies that any zero velocity particle will be measured by the processor as having the down-mix frequency. Any frequency value measured over the down-mix frequency corresponds to positive velocity and any value less than the down-mix frequency corresponds to negative velocity.

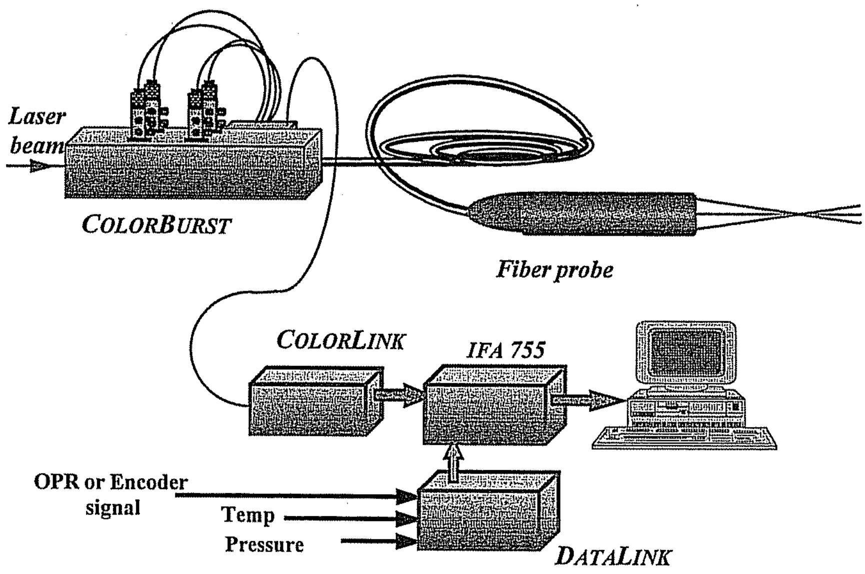
Modern Fiber Optic LDV Systems

Components of the System include:

- Air or water cooled Laser
- Integrated Transmitting Optics
- Fiber Optic Probes
- Integrated Receiving Optics/ Electronics
- Signal Processors
- Windows based Acquisition/Analysis

The modular approach to LDV of the earlier days is now replaced by integrated systems approach. As personal computers became more affordable and faster, the entire system runs under computer monitor and control. This minimizes the time of set up and ensures accuracy of the measurement. Windows based acquisition packages with on-line help are now available to further simplify the measurement process.

Integrated 2D Fiber Optic LDV System



New integrated fiber optic LDV systems are very compact and offer enhanced accuracy and a simplified set-up. The main components of the integrated systems include:

COLORBURST transmitting optics module which provides three pairs of beams, one beam of each pair is frequency shifted.

Two *Couplers* per color enable the beams to be launched into fiber probes.

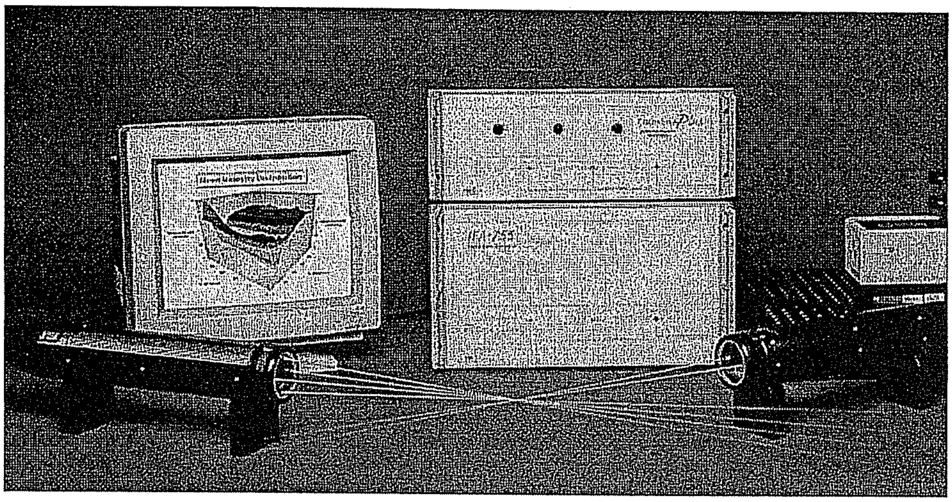
2d (four beam) and 1d (two beam) fiber optic probes are available for 1d, 2d or 3d measurements. In addition for certain applications, 5 beam 3d probes are available.

Scattered light collected in back scatter is routed through a multi-mode fiber to the COLORLINK *Plus* multichannel receiver, which provides filtering, color separation, photo detection and frequency down mixing all under software control.

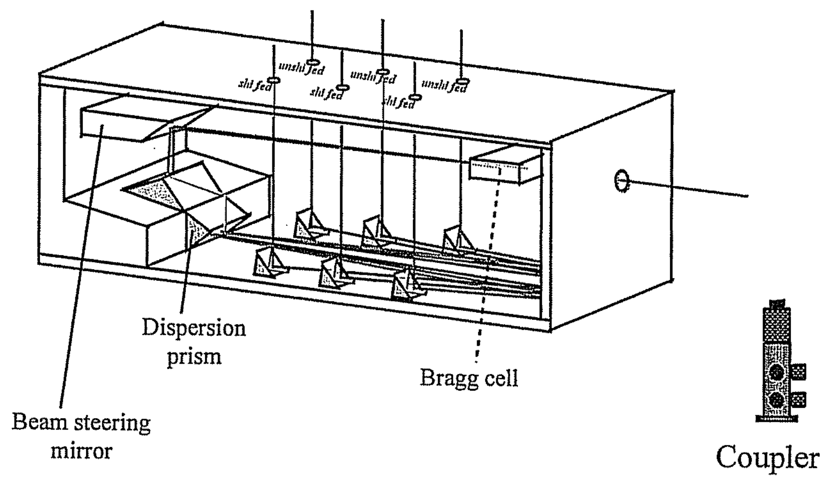
The signals from the receiver are processed using the *IFA* series digital signal processors and FIND-W/PACE Windows based software packages. DATALINK is used to synchronize data from any transducer or other external sources with LDV measurements.

For measurements in rotating machinery, the RMR (Rotating machinery Resolver) module of DATALINK is used. The input to the RMR module could be a once-per-rev signal (OPR) or the output of an incremental shaft encoder.

3 Component LDV System



COLORBURST Multicolor Beam Separator

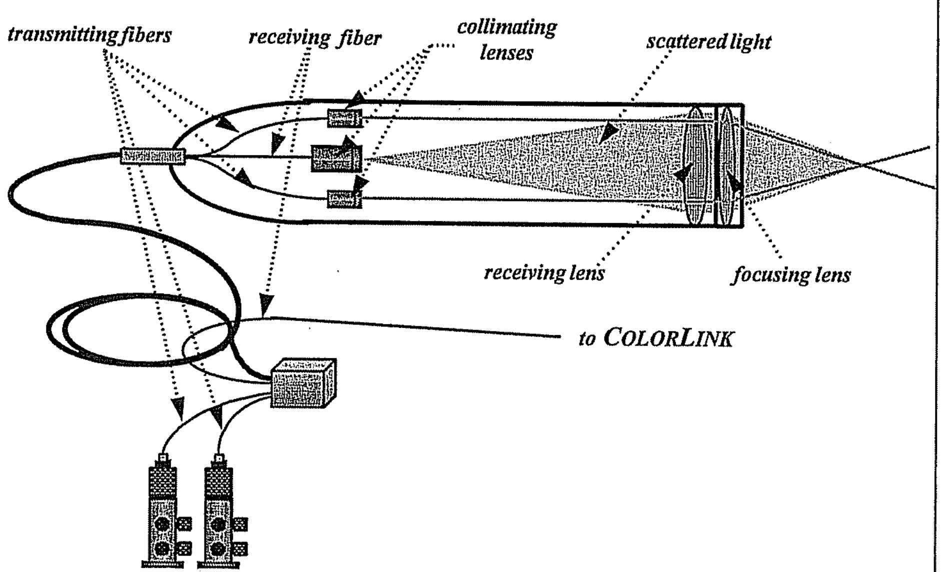


Performance and safety are the two design criteria for the COLORBURST transmitter module. In addition to the laser, two other safety shutters are provided, one at the input of the COLORBURST and one at the base of each coupler. In addition a neutral density filters module at the input ensures attenuation of the beam for ease and safety of set up.

The multicolor input beam from an Argon-Ion laser first passes through the Bragg cell. The angle of the cell is adjusted so that it provides two equal intensity multicolor beams; one shifted (40 MHz) and the other unshifted. The two beams, after going the length of the unit, are then deflected to pass through dispersion prisms to separate the colors. After again traversing the length of the unit, prisms and mirrors reflect the beams back to six individual mirrors that direct the beams to the appropriate exit holes. From there the beams enter fiberoptic couplers or standard optics. The unit can be used for 1-, 2-, or 3-component systems.

With only Bragg cell angle and mirror adjustments, COLORBURST is easy to set up.

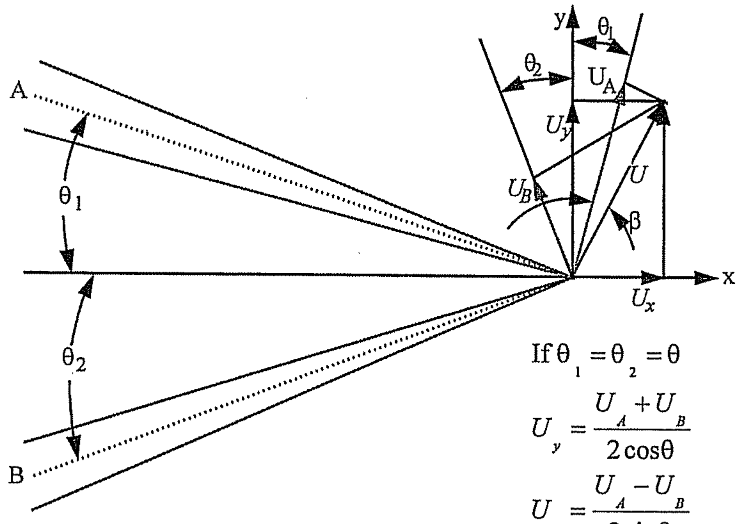
Fiberoptic Probe



Standard fiber optic probes come with a 10 m cable separating the final lens from the laser and transmitting optics. This lends great flexibility to the system and simplifies traverse requirements. Probes from 15 mm diameter to 83 mm diameter are available with focal distances varying from 60 mm for the smallest probe to 2000 mm for the larger probe with beam expander. The 83 mm probe is the most versatile with interchangeable lenses and individual beam steering. Stainless bodied probes are available for under water use.

All fiber probes operate in back scatter. Retro-reflectors can be used (if needed) to reflect forward scatter light on to the back scatter fiber to further enhance data rate and signal quality. Special fiber optic probe designs are available for Tow tank, wave tank, combustion and cryogenic applications.

Three Component Measurements



If $\theta_1 = \theta_2 = \theta$

$$U_y = \frac{U_A + U_B}{2\cos\theta}$$

$$U_x = \frac{U_A - U_B}{2\sin\theta}$$

The best way to make three-component velocity measurement is to use two probes, where the optical axis of the probe to measure the third component of velocity is perpendicular to that of the two component probe. Unfortunately, access and/or traversing difficulties often make this arrangement impractical.

A viable option is to place the axes of both the probes in the same plane with a large included angle (typically 45 deg. or larger). With this arrangement one component (U_z) can be measured directly and the other two (U_x and U_y) are calculated from two non-orthogonal measurements (U_a and U_b). The larger the included angle between the two probes, the larger is the accuracy of U_x.

U is the resultant vector in the x-y plane

For $\theta_1 \neq \theta_2$, the general equations are:

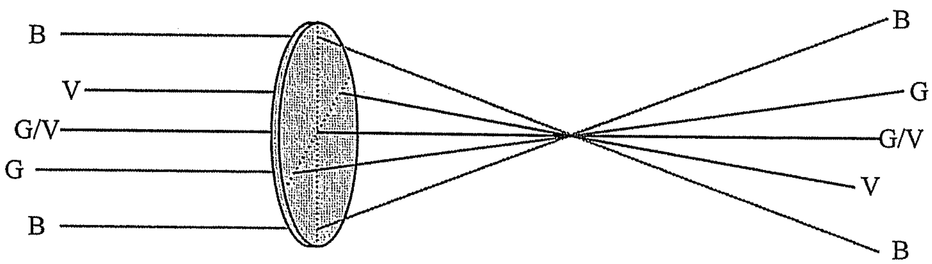
$$U_x = \frac{U_A \sin\theta_2 + U_B \sin\theta_1}{\sin(\theta_1 + \theta_2)}$$

$$U_y = \frac{U_A \cos\theta_2 - U_B \cos\theta_1}{\sin(\theta_1 + \theta_2)}$$

These equations permit transforming any two velocity measurements in a plane into any two orthogonal components in the same plane.

3 Component Co-axial probe

3 Color Arrangement



Even though a two probe arrangement with a large included angle between probes is desirable for accurate 3d measurements, some applications with limited optical access (e.g., 3d measurements through the head of an IC engine) require a single lens system. A three color arrangement is used with 5 beam fiberoptic co-axial probe systems for just such measurements.

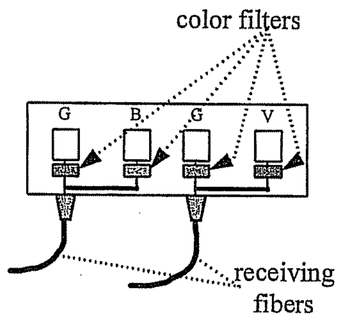
The center beam is a combination of green and violet beams. The on axis and horizontal component of velocity are measured using the green (G), violet(V) and the green-violet(G/V) beams. In order to improve the on-axis velocity component accuracy, a short focal distance lens is used with the five beam probe.

Single lens five beam probes are also ideal for 3d velocity profile mapping in water channel flows where the probe is located outside. A two probe arrangement does not work very well in such flows as the two measurement volumes get uncrossed when traversed normal to the test section wall.

ColorLink Plus system

- Can have up to 4 PM tubes
- Ability to select *any* frequency shift value

- Photo-multiplier tube (PMT)
  - large bandwidth 150 MHz
  - High gain PMT
- Special shift values for high speed flows



- Completely computer controlled

The ColorLink Plus system is a computer controlled integrated receiver that converts scattered light received through fibers into electrical signals. These signals are down mixed before they are sent to the signal processor. ColorLink Plus can be used with 1, 2, or 3 component LDV systems. The main components include color filters, color separators, PMTs, and down mix electronics.

While choices exist, generally the green line is used for 1-component measurements, green and blue for 2-component measurements, and green, blue and violet for 3-component measurements. The green and blue arrive on the same receiving fiber, with color separation taking place in the unit. Narrow band optical filters are provided for each photomultiplier (PMT) to prevent any possible signal contamination from other colors.

The voltage of the PMTs (as with other parameters such as frequency shift) can be controlled from the computer. Effective shift frequencies after downmixing vary from 0 to 10 MHz in a 1, 2, 5 sequence starting at 2 kHz. Besides the direct 40 MHz shift, positions of –10 and –20 MHz are provided for high-speed flows. The ColorLink Plus also has the ability to provide *any custom frequency shift* value.

ColorLink Plus allows up to 4 PMTs. This provides the capability to measure 3 components of velocity and particle size simultaneously. In addition, it has outputs to drive the power amplifier for up to three Bragg cells. Only one is used with the ColorBurst Multicolor Beam Separator.

Signal Processor - Key requirements

Should be able to:

- Detect bursts based on SNR
- Fill the block with good data
- Optimally sample each burst (independent of the dynamic range of the flow)
- Ability to always use a large block of data
- Center the burst and use the data from the middle portion of the burst
- Ability to collect the required number of samples for the signal bursts

Digital signal processing is the main stay of LDV signal processing. The ability of DSP in extracting signal frequency from noisy background is unsurpassed. Not all digital processors perform equally as there are several key design criteria that differentiate the processor's ability to maximize data rate and signal extraction capability. The first among these is a robust burst detector that can identify the presence of a Doppler burst in a noisy signal. This component is discussed in the next slide.

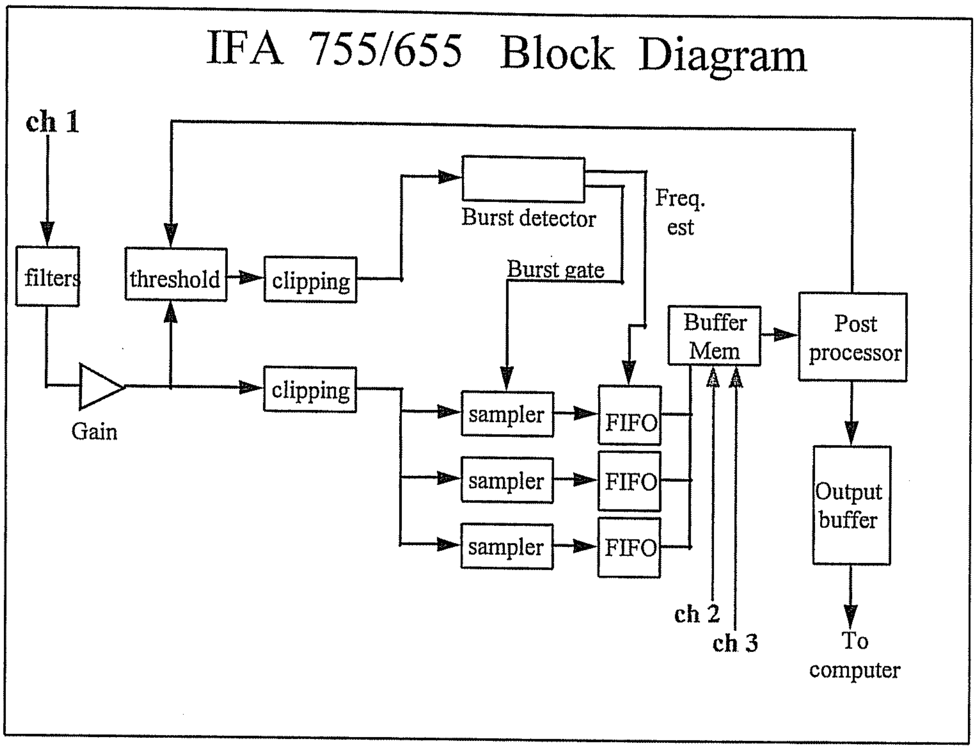
Once a burst is detected, it is important to employ a large sample size and use it optimally around the center of the burst where the SNR is the maximum. Equally important is the ability to change the sample rate dynamically for each and every burst depending on its frequency. This will allow the processor to spread the sample size across the burst so that that there are adequate samples/cycle over adequate number of Doppler cycles.

IFA 655 and 755 processors are developed using these design criteria.

Impact of type of Burst Detection

		Method of Burst Detection	
Signal Source	Signal Amplitude	Amplitude/ Envelope Based	SNR Based
Small Particles	Small	Rejects	Detects (Passed on for frequency estimation)
Large Particles	Large	Detects (Passed on for frequency estimation)	Detects (Passed on for frequency estimation)
Reflection	Large	Detects (Passed on for frequency estimation)	Rejects
Other Types of Noise	Small/ Large	Detects some (Passed on for frequency estimation)	Rejects

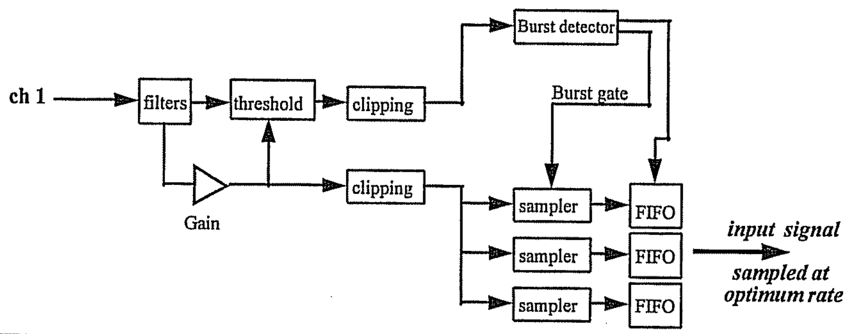
Design of SNR based burst detector is crucial to any digital signal processor. IFA processors employed the first such detector. In addition to detecting the bursts based on SNR, the detector can also provide the beginning and the end of the burst and an approximate frequency of the burst. The former information is used to center the samples around the center of the burst and the latter is used to pick the most optimum among several sampling rates used to sample the burst in parallel. The optimum sampling rate is one that allows 10-20 samples/cycle over the center 10-15 cycles of the burst. The key is to employ as many of the 256 samples as possible.



The down mixed Doppler signal from Colorlink Plus is sent to the IFA processor. The signal is filtered through band pass filters selected automatically by the processor (based on maximum data rate) or manually by the user. The signal is then amplified and clipped. A minimum threshold serves to supress any background noise. The clipped signal is sent to a burst detector and multiple parallel samplers at the same time. The burst detector detects the burst by performing a 16 sample auto-correlation of the clipped signal. It also provides an approximate frequency of the burst and the beginning and the end of the burst. This information is used to pick the center 256 samples of the burst sampled at an optimum rate. Optimum rate ensures at least 10-20 samples per cycle over 10-15 cycles around the center of the burst. These samples are sent to the main burst correlator which performs a 256 sample autocorrelation function.

Burst Detector

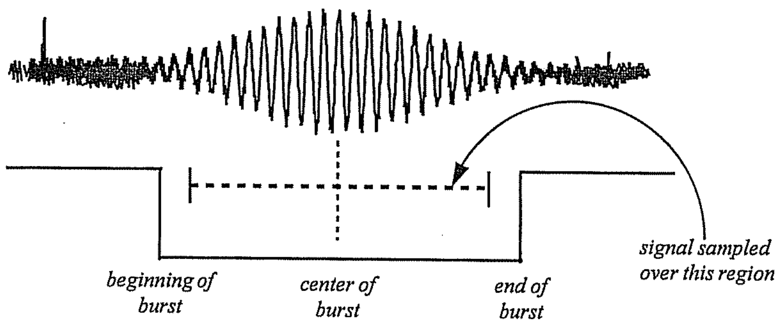
- IFA 755 Burst detector (Patented)
  - determines the approximate frequency of a burst
  - determines the beginning and end of burst and center of the burst (using Burst gate signal)
  - dynamically selects the optimum sampling frequency (using the approximate frequency value) so that ***<u>the same burst</u>*** is sampled at the optimum rate (from the multiple samplers used) !!!



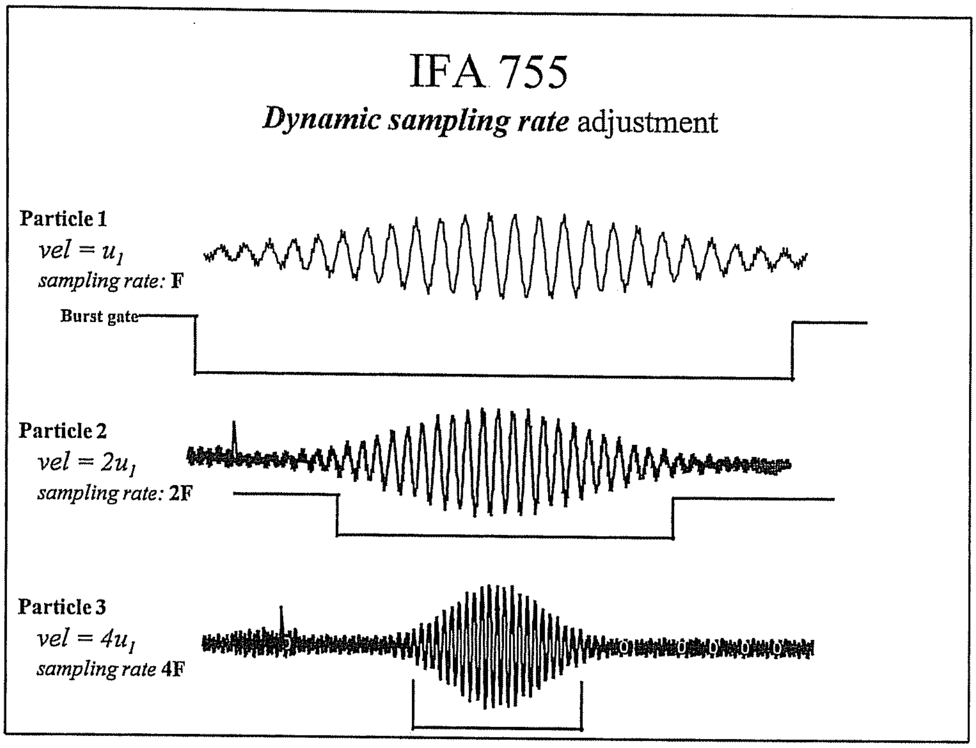
The burst detector in combination with the multiple samplers provide the ability to sample the incoming signals at the optimum rate !

Digital Burst Autocorrelator IFA 755

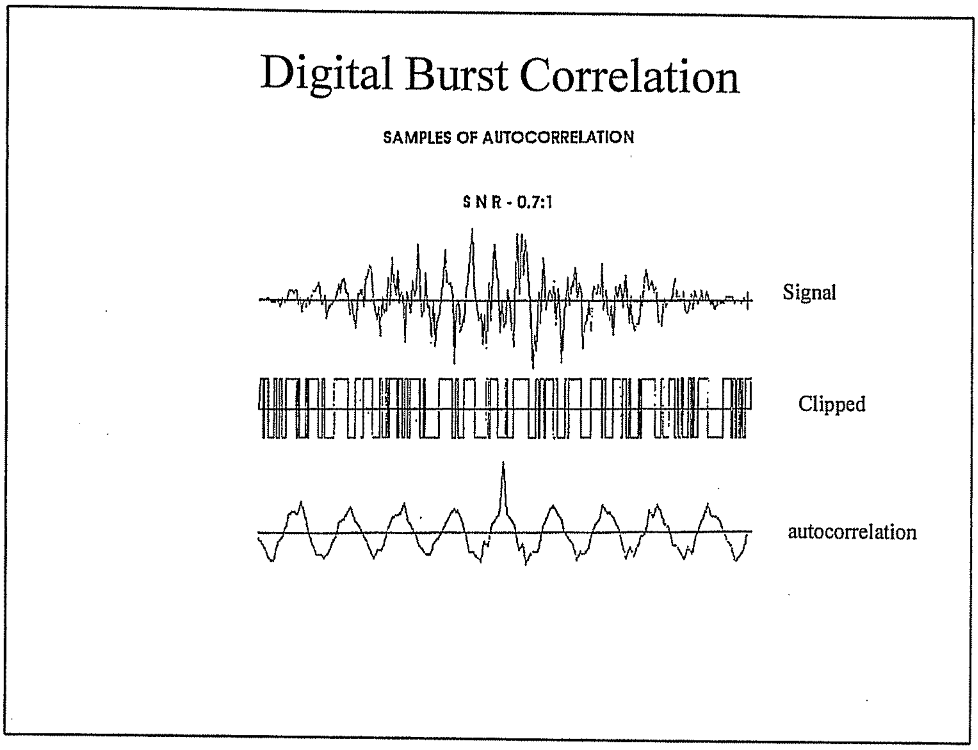
- IFA 755 or 655 Burst Detector
  - center portion of the signal is sampled at the optimum rate
    - center portion of the signal has the best signal quality
    - burst centering is used to sample the middle portion of the burst
    - collects the large number of samples ***always from all bursts***



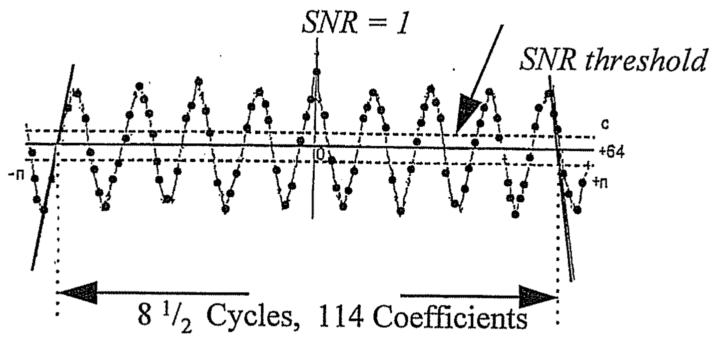
The burst detector also identifies the beginning and the end of the burst. From these, the center of the burst where the signal quality is best is located. Samples are collected from the middle portion of the burst, starting from the center and moving outwards, as shown.



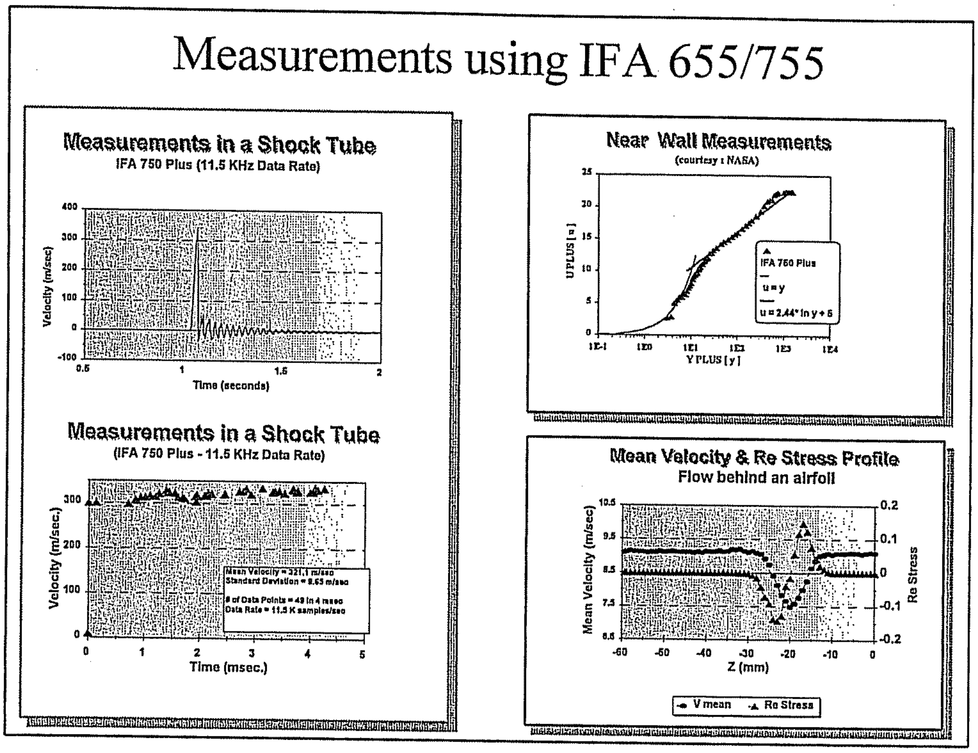
As the velocity of the flow changes (from one burst to the next) the sampling rate is also dynamically changed. This is done automatically (bust detector provides the optimum sampling rate information) so that the the processor can collect the same maximum number of samples in all these cases.



A 256 sample autocorrelation performed on the optimum samples yields discrete auto correlation coefficients. The vertical axis of correlogram is a measure of the SNR of the burst.



Several validation criteria are employed to ensure accurate frequency measurement. Criteria include a minimum number of correlation coefficients, skewness of the correlation function, SNR etc. The resolution of the correlation function is enhanced by linear interpolation at the ends to determine the first and last zero crossings of the correlation function. This is analogous to fitting a curve of the peaks of discrete spectral lines to obtain the Doppler frequency. While in a FFT technique curve fitting is done where the slope is flat (resulting in a poor resolution), interpolation in a correlation function is done where the slope is maximum thereby enhancing resolution. Once the first and the last zero crossings are established and the number of correlation cycles and coefficients is known, the Doppler frequency can be easily calculated.



Measurements in high speed, transient flows

Flow in a shock tube represents a short duration, high speed, large dynamic range flow. Measurements using a Digital Burst Correlator gave an average data rate of 11.4 kHz. The system was able to characterize the shock passage (flow velocity of about 340 m/sec) and also the reflection of the shock from the ends of the tube. The processor was able to capture the velocity variation from 330 m/sec to -34 m/sec occurring in a fraction of a second

Measurements in a boundary layer

The ability of the Digital burst Correlator to extract information from a noisy signal is demonstrated by the measurements carried out in the region very close to the wall.

The velocity measurements agree very well with the law of the wall and logarithmic law. It should be noted that the last 2 or 3 points (closest to the wall) were obtained with the measuring volume "buried" in the wall.

Measurements in a wake field

The LDV system was operated in the coincidence mode to measure all three components of velocity simultaneously. The ability of the processor to make accurate instantaneous velocity measurements is exhibited from the ability to obtain Reynolds stress variation accurately. The variation of the axial velocity mean (V_{mean}) plotted as a function of Z shows the velocity defect in the wake field behind the airfoil.

Features of FIND - W

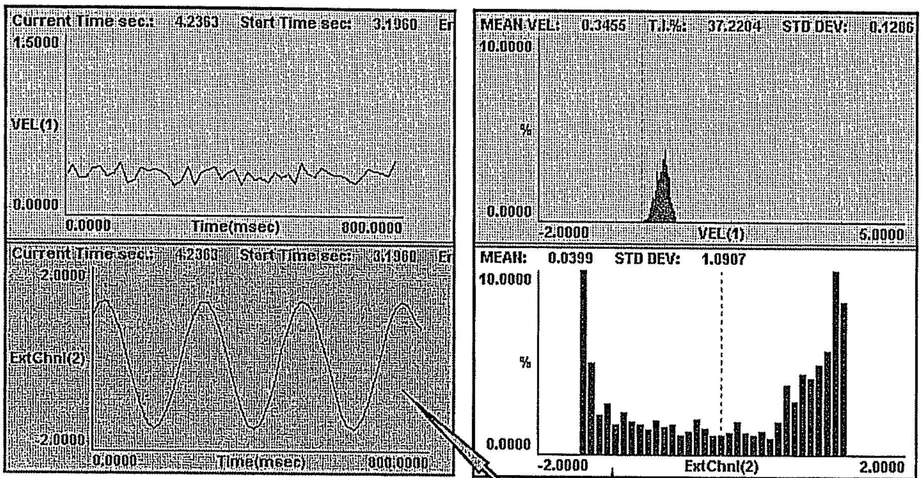
- ***First*** **commercially available Windows based package for LDV**
- **True multiple *real-time* displays**
- **Real-time display of original or transformed data**
- **Ability to rerun the experiment**
- **Built-in traverse grid generation package**
- **System optimization during automatic traverse**
- **Ability to use external traverse**

FIND-W is the data acquisition and analysis package in a Windows environment. The software controls and monitors the signal processor, PMT's, down mix electronics to provide reliable experiment set up. The LDV signals are acquired along with any optional external data (Temperature, pressure etc.). Velocity and frequency information is obtained in real-time in the form of time history and/or histograms. Detailed post processing, spread sheet capability and graphics are included. FIND-W also allows the user to control other traverses if a driver is available.

Features of FIND - W

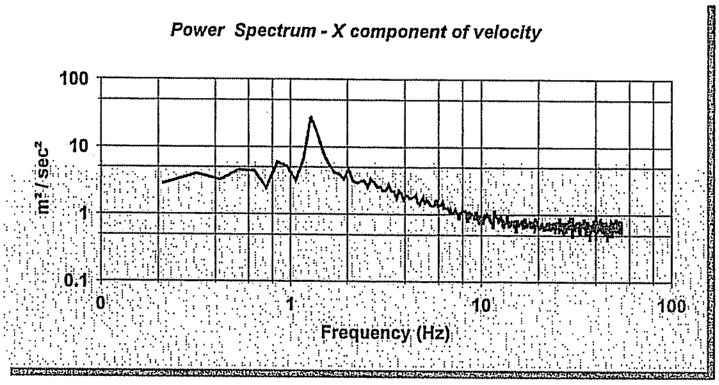
- Ability to select custom frequency shift values
- Built-in spread sheet and graphics capability
- Coordinate transformation - matrix approach
- Power spectrum of the velocity field
- Collect external (i.e., non-LDV) data using DATALINK
- Real-time display of external data
- Lab notes - to make a report or keep notes and comments
- On-line help
- LOG book to keep track of program status

FIND-W *Real-time* Displays



□ Real-time displays of velocity and an external sinusoidal input signal

Features of FIND - W
Power spectrum



- Results using the random correlation approach to compute the power spectrum of flow velocity.

Features of FIND - W

Built-in Spread sheet

Statistics View: Cummulative Results

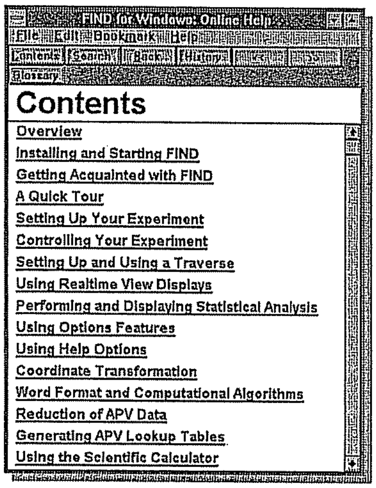
Run Options | Tabular Output | Cummulative Results | Graphical Output

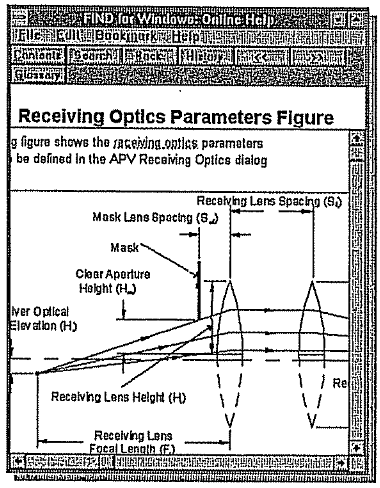
	X	Y	Z	U pts	pt	W pts	U mean	
star0001	40.0000	1.23	0.0010	1000	0	0	16.4091	0
star0002	40.0000	1.1	0.0010	1000	0	0	16.4093	0
star0003	40.0000	1	0.0010	1000	0	0	16.4095	0
star0004	40.0000	0.9	0.0010	1000	0	0	16.4049	0
star0005	40.0000	0.8	0.0010	1000	0	0	16.4062	0
star0006	40.0000	0.7	0.0010	1000	0	0	16.4055	0
star0007	40.0000	0.6	0.0010	1000	0	0	16.4051	0
star0008	40.0000	0.5	0.0010	1000	0	0	16.4047	0
star0009	40.0000	0.4	0.0010	1000	0	0	16.4034	0

- **Detailed cumulative statistics (from traversing) is directly available in the spread sheet form**
- **Spread sheet - similar to Excel in nature**
- **Built-in graphics package and spread sheet**

Features of FIND - W

On-line HELP





Features of PACE

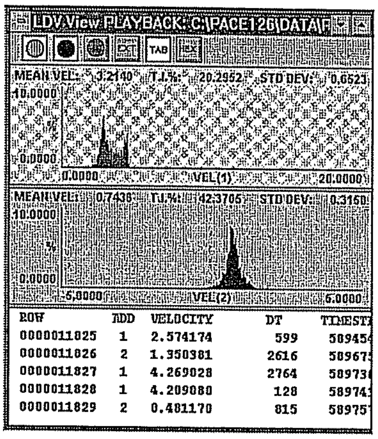
- ***First* commercially available Windows based data analysis package for periodic flows**
- **Easy generation of data windows**
- **True multiple *real-time* displays**
- **Real-time display of phase-averaged flow properties**
- **Real-time display of original or transformed data**
- **Ability to rerun the experiment**
- **Built-in traverse grid generation package**
- **System optimization during automatic traverse including data window modifications**
- **Phase-averaged statistics including Window averaging**

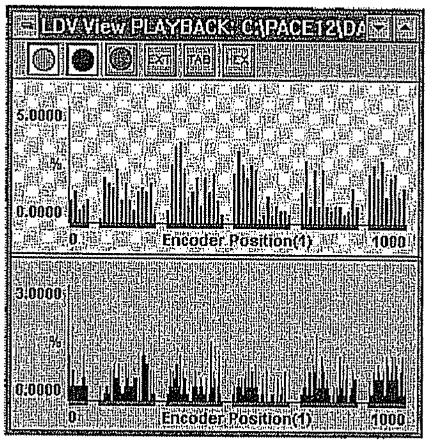
PACE for Windows is a completely self contained control, acquisition, analysis and analysis package designed for applications involving periodic flows such bio-fluid flows, rotating machinery flows, IC engine flows etc. PACE provides all the 3d velocity measurement and display capability of FIND In addition, it collects data as a function of a "Once per rev" (OPR) signal obtained from the experiment. All the data thus obtained is phase averaged and displayed in convenient real time graphics. In conjunction with the "Rotating machinery resolver" (RMR) hardware, PACE can also deal with cycle to cycle variations.

Features of PACE

- **Cycle-to-cycle variation analysis**
- **Ability to use external traverse**
- **Ability to select custom frequency shift values**
- **Built-in spread sheet and graphics capability**
- **Coordinate transformation - matrix approach**
- **Collect external (i.e., non-LDV) data using DATALINK**
- **Real-time display of external data**
- **Lab notes - to make a report or keep notes and comments**
- **On-line help**
- **LOG book to keep track of program status**

Real-time displays





- Histograms - Velocity or Frequency, External Data
- Data arrival vs. Encoder position
- Tabular display
- Time history

TSI®

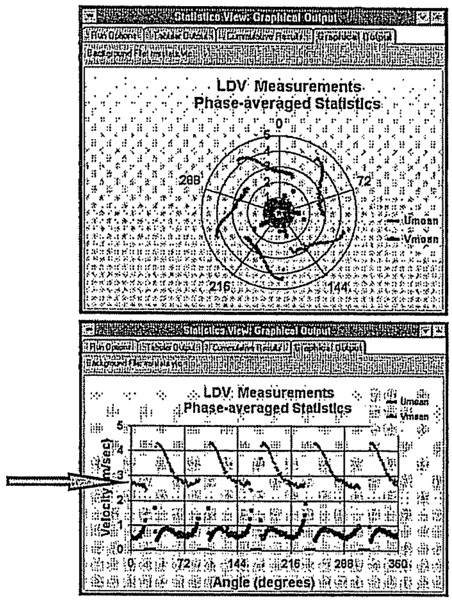
Graphical Display

Phase-averaged velocity statistics

Displays generated using built-in graphics

(shows only Umean and Vmean)

- Can be displayed in a variety of formats
  - example shows displays in polar diagram and X-Y (scatter) plot formats
- Display shows graphs starting at encoder position zero
  - ***Display offset*** = zero.



TSI®

Table of contents

Evolution of Anemometry Technology

- Front panel setting of operating resistance and frequency response (1050, 55M, 56C)
- Introduction of TSI's ***IFA 100***, the first computer monitored anemometer, RS232 set-up of signal conditioner, frequency response tuning still necessary at the front panel
- Streamline, fully computer controlled, frequency response tuning still necessary via mouse, and dependent on sensor, cable etc.....
- ***FlowPoint***, first system with no tuning, Lower response
- New TSI's ***IFA 300***, fully computer controlled, frequency response tuning eliminated, highest frequency response guaranteed, independent of sensor.

Over the last 35 years, TSI introduced five generations of thermal anemometer systems, in response to our customers' requirements. All the successive generations of anemometers were designed to simplify set up and operation so that the user can focus on the results. TSI is the first and the only company which offers anemometers that ensure stable operation and a high frequency response without the need for bridge tuning.

TSI offers complete thermal anemometer systems which include a cabinet, power supply, anemometers, signal conditioners, A/D modules, Windows based comprehensive acquisition/analysis/calibration software, variety of standard and custom probe designs, manual and automatic calibrators. Calibration service at TSI is also available.

Limitations of existing anemometers

- Frequency response tuning required, usually done with a mouse on a PC, a tedious, time consuming set up
- Tuning is done at one velocity
- Anemometer bridge still may oscillate leading to probe damage
- Set up required when probes and cables are changed
- Different bridges required to obtain high frequency response
- Square wave testing is required

An un-optimized anemometer could break into oscillations as the velocity goes up and sometimes large amplitude oscillations can damage sensors. Un-optimized anemometer also causes significant errors in the measurement of turbulence. Frequency response optimization in a system is therefore essential to ensure oscillation free operation and flat response to all frequencies in the flow.

In all available anemometers except TSI's FlowPoint and IFA 300, this optimization is done through a tedious set up where a square wave is introduced at the top of the bridge and the response of the bridge to the square wave is optimized using controls available through a mouse or at the front panel. This optimization is time consuming and has to be repeated when there are changes in the probes used, in the maximum velocity of interest, and in the cable length.

Both FlowPoint and IFA 300 provide oscillation free operation ensuring required frequency response without the need for tuning.

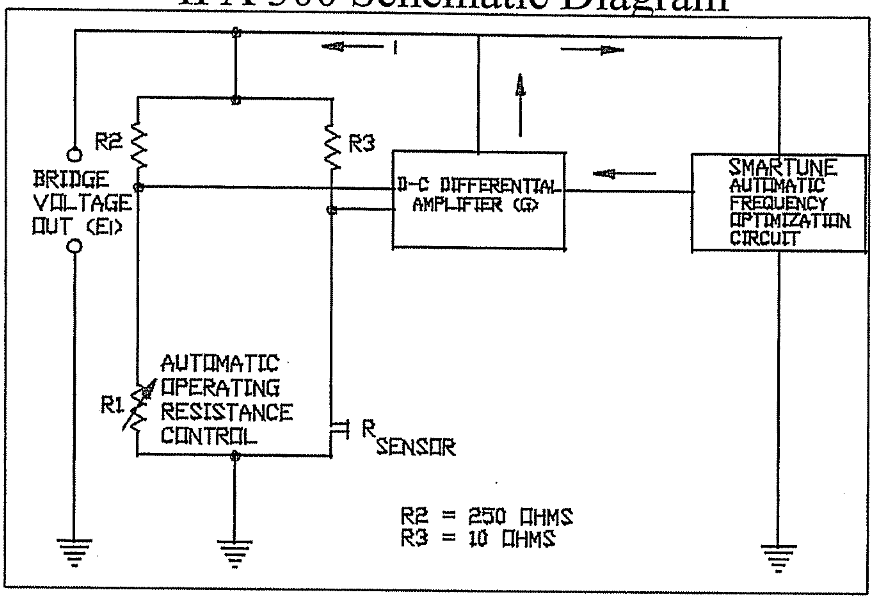
IFA 300 Development

- Patented SMARTTUNE Technology eliminates need for bridge tuning
- SMARTTUNE circuit automatically compensates for changes in supports, cable lengths, sensor type, velocity changes
- Square wave testing is not required but is provided for any verification tests
- Oscillation free operation from low velocities all the way to supersonic flows
- Single bridge covers all applications
- No set up necessary

IFA 300 represents a breakthrough in anemometry technology and contributes significantly to simplify system set up, calibration, data acquisition and analysis. IFA 300 is designed to provide high frequency response without the need for bridge tuning, square wave testing etc. This is true for a variety of probes, and for different factory set cable lengths and for different velocities.

While FlowPoint provides 10 KHz response and designed for all water and lower speed air applications, IFA 300 with >300 KHz response is the top of the line system for all practical applications.

IFA 300 Schematic Diagram



Patented SMARTTUNE circuit constantly monitors the bridge voltage and feeds a signal to the amplifier circuit, thereby maintaining the frequency response based on the operating temperature and sensor type. It also prevents oscillations which damage the sensor. No tuning or verification is necessary, but a square wave of variable frequency and amplitude is built in if the user chooses to observe the optimum response of the system displayed on a oscilloscope screen.

SMARTTUNE allows the system to maintain optimum response without oscillation for a variety of standard and custom sensors.

IFA 300 System Components

Anemometer	Signal Conditioner	A/D Converter	Computer & ThermalPro Software
•Automatic resistance measurement 0.1% ± 0.01 ohms •Automatic operating resistance control •SMARTTUNE frequency optimization circuit •>300 KHz response •Single bridge	•Offset: 0-10 V 10 mV steps •Gain: 1-1,000 •High Pass: 0, 0.1,1,10 Hz •Low Pass: 12 Hz - 1MHz, 13 settings, -60 dB/decade	•12 bit •1 MHz throughput •Sample & Hold	•1, 2, 3 D Statistics •Automatic Traverse •Probe Calibration •Quasi real time display for velocity, flow angle

IFA 300 anemometer system consists of a *cabinet* that accommodates up to eight constant temperature *velocity or constant current temperature modules* (for high frequency temperature fluctuation measurement). It can also accommodate a flow control board for the auto-calibrator. For standard set up two cabinets can be stacked in a 16 channel system. Even 32 channel systems are possible. Each velocity/temperature module comes with a built in *signal conditioner* which can filter out noise and can offset/amplify the incoming signal to optimally use the 12 bit resolution of the A/D converter. The *A/D converter* offers a through put of 1 MHz (with up to 750 KHz of A/D on a single channel) with simultaneous sample/hold. *ThermalPro*, a Windows based control/calibration/acquisition/analysis/display software provides comprehensive software for complete experiment management. ThermalPro is a 16 channel program with single and multi-sensor velocity analysis. In addition it can also acquire/analyze data relating to temperature fluctuations, wall shear stress, heat flux and other related properties.

ThermalPro Control & Acquisition

IFA 300 Control	Traverse Control	Probe Calibration	Data Acquisition
•Resistance measure	•X, Y, Z Axis	•1, 2, 3D probe	•A/D sampling rate
•Operating resistance	•Automatic traversing matrix	•Velocity, yaw & pitch	•Number of samples
•Signal conditioner		•Polynomial Curve fitting	•Hardware diagnostics
		•Remote flow control	

ThermalPro software provides control of the anemometer, signal conditioner, A/D converter, auto-calibrator and traverse functions in a friendly Windows based environment.

Anemometer functions such as resistance measurement, operating resistance set up are all set through ThermalPro. User selected gain/offset/filter values can be implemented or the software can select optimal parameters automatically. For automatic calibrators, the entire speed calibration process including flow control is control by ThermalPro.

ThermalPro includes traverse control for a variety of TSI recommended traverses. In addition, existing traverse's control can also be built into ThermalPro easily.

ThermalPro Data Analysis/Display

Statistical Analysis

- U, V, W Mean
- Turbulence, angle
- Shear stress, cross correlation
- Automatic temp. correction

Quasi Real-Time Display

- U, V, W, angle histogram
- U, V, W, angle vs time

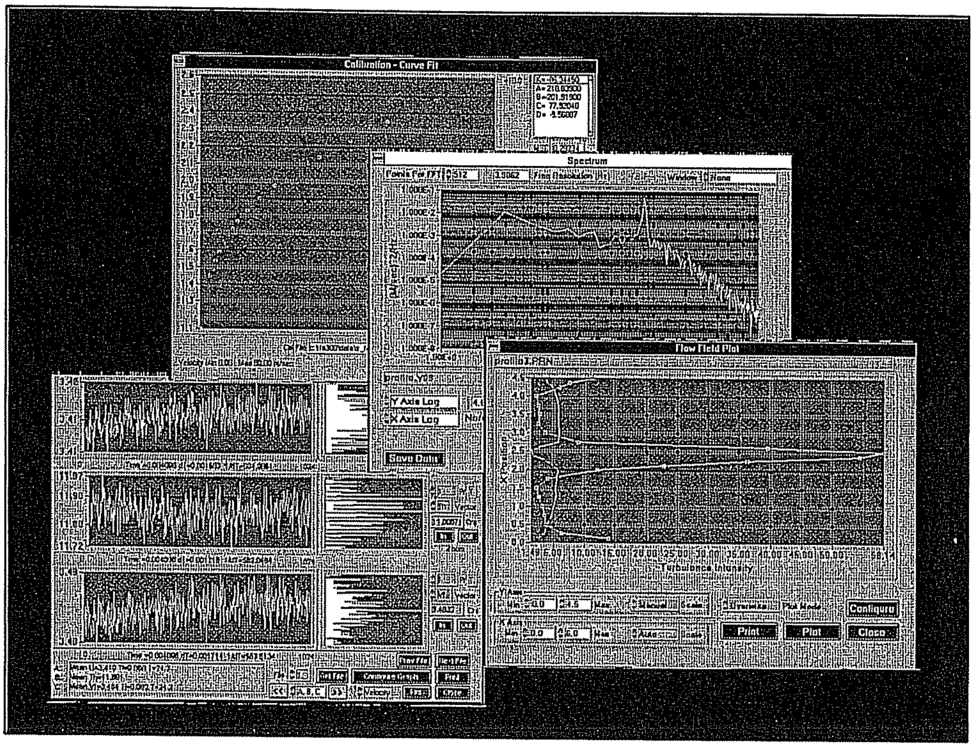
Spectrum & Correlation

- Power spectrum, U, V, W
- Autocorrelation, U, V, W
- Table, graph, file

Flow Field Plot

- U, V, W statistics vs Coordinates
- Table, graph, file

ThermalPro provides comprehensive data analysis capabilities both in near real time and in post processing. In addition to velocity time history of all velocity components, histograms, all the higher order moments can be calculated and displayed. Power Spectrum and correlation can be calculated and displayed. All the data from raw voltages to processed numbers is stored and available in formats that can be easily exported to other programs. High frequency velocity and temperature measurements can be correlated.



Graphics capability of ThermalPro includes calibration and related error plots, velocity component time history, histograms, Power spectrum/correlation plots, flow field profile plots of all statistics. In addition, the data is available to be exported to spread sheet and other programs.

References

- Fundamentals of Hot Wire Anemometry, Charles Lomas, Cambridge University Press, 1986
- Hot-Wire Anemometry, A.E. Perry, Clarendon Press, Oxford 1982
- Bibliography Of Thermal Anemometry, Peter Freymuth, 1992, TSI Inc.
- Hot-Wire Anemometry: Principles and Signal Analysis, H. H. Bruun, Oxford Science Publications

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