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MEASUREMENT CAPABILITIES OF A ONE-DIMENSIONAL LDV SYSTEM

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16. ABSTRACT

The capability of a single component laser Doppler velocimeter (LDV) system for the measurement of three dimensional mean and turbulent flow statistics is investigated. Sets of general equations defining the parameters measured by a single component LDV system are derived. Solutions to the equations for different configurations of a single forward scatter LDV system show that three dimensional mean velocity measurements can be made with a minimum restriction on the precision for detecting the Doppler frequency. Measurements of the three dimensional RMS, cross products and correlation parameters are shown to require a significantly higher precision in the Doppler frequency detection.

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INTRODUCTION

A single component laser Doppler velocimeter (LDV) system provides a technique for measuring one dimensional mean and turbulent velocities in fluid flows. It is shown here, that the single component LDV system also is capable of determining the additional information of two and three dimensional mean and turbulent flow characteristics. This capability is illustrated by the derivation of several sets of equations which define the mean and turbulent parameters that a single component LDV system measures in a three dimensional flow field. It is shown that by making LDV measurements from several different independent angular arrangements, sets of independent simultaneous equations are defined and can be solved to obtain three dimensional mean, RMS, cross-products and correlation parameters of the fluid flow. This procedure assumes that the independent measurements are made at the same location in the flow and that the flow is statistically stationary.

Solutions to the sets of simultaneous equations were considered for a single component forward scatter LDV system, to assess the precision with which the Doppler frequencies must be measured in order to obtain an accurate measurement of the three dimensional flow paramenters. It was found that for the angular arrangements considered, the three dimensional mean flow quantities would be the least difficult measurement, while the RMS, cross-products and correlation parameters become more difficult. This difficulty is due to a more stringent requirement imposed upon the precision to which the Doppler frequencies must be evaluated.

LDV SYSTEM AND DEFINING EQUATIONS

The laser Doppler velocimeter employs the phenomena of Doppler shifting of light frequencies to measure the velocities of small particles suspended in fluid flows. For nonrelativistic particle motion, the Doppler shift may be shown to be linearly related to the velocity of a particle in a direction dependent on the geometrical angular arrangement of the optical paths within the system. Figure 1 shows three typical optical arrangements that are used in single LDV systems. For each of these systems a general equation can be written which relates the instanstaneous Doppler frequency measured by the system to the instanstaneous velocity components of a cartesian coordinate system. This equation is written as

$$\lambda F_i(t) = a_i\, U(t) + b_i\, V(t) + c_i\, W(t) \tag{1}$$

Where U, V, and W are the velocity components in the X, Y, and Z directions, λ is the laser wavelength, F_i is the Doppler frequency shift, a_i, b_i, c_i are coefficients relating the geometrical arrangement of the LDV system to a cartesian coordinate system, and the subscript i denotes the measurement number for a given system configuration, i.e. $i = 1, 2, \cdots n$.

Dividing each of the velocities and the Doppler frequency into a mean and a fluctuating component, such as:

$$U(t) = \overline{U(t)} + U'(t) \tag{2}$$

Equation 1 becomes:

$$\lambda(\overline{F_i(t)} + F_i'(t)) = a_i\left[\overline{U(t)} + U'(t)\right] + b_i\left[\overline{V(t)} + V'(t)\right] + c_i\left[\overline{W(t)} + W'(t)\right] \tag{3}$$

The overbar indicates the quantities mean value or time average, which may be expressed mathematically as:

$$\overline{(\ )} = \frac{1}{T} \int_0^T (\ )dt \tag{4}$$

and from the definition in (2) $\overline{(\ )'(t)} = 0$

Taking the time average of Equation 3 yields:

$$\lambda\, \overline{F_i\ (t)} = a_i\ \overline{U\ (t)} + b_i\ \overline{V\ (t)} + c_i\ \overline{W\ (t)} \tag{5}$$

Where $\overline{U(t)}$, $\overline{V(t)}$, and $\overline{W(t)}$ are the mean velocities in the X, Y, and Z directions and $F_i(t)$ is the mean Doppler frequency shift for a single LDV system in a configuration defined by the a_i, b_i, and c_i coefficients.

From Eq. 5 it is seen that in a general single LDV measurement,there are three unknown velocity components. These velocities may be determined by making LDV measurements at the same position in the flow field and changing the geometrical arrangement of the system for three independent measurements. The defining equations for such a set of measurements are written as:

$$\lambda\, \overline{F_1\ (t)} = a_1\ \overline{U(t)} + b_1\ \overline{V(t)} + c_1\ \overline{W(t)} \tag{6}$$

$$\lambda\, \overline{F_2\ (t)} = a_2\ \overline{U(t)} + b_2\ \overline{V(t)} + c_2\ \overline{W(t)} \tag{7}$$

$$\lambda\, \overline{F_3\ (t)} = a_3\ \overline{U(t)} + b_3\ \overline{V(t)} + c_3\ \overline{W(t)} \tag{8}$$

By solving Eqs. (6), (7), and (8) simultaneously the three mean velocity components may be obtained.

Since the three indicated measurements must be conducted at three different times,the flow must be stationary in order for the procedure to yield meaningful and accurate results. For a statistically stationary process, the time average of a quantity is independent of the placement of the interval over which the computation is made. This is expressed mathematically as

$$\frac{\partial}{\partial \beta}\left(\frac{1}{T} \int_\beta^{\beta+T} (\ )dt\right) = 0 \tag{9}$$

An equation for the fluctuating velocity components is obtained by subtracting Eq. 5 from Eq. 3. This yields

$$\lambda F_i'(t) = a_i U'(t) + b_i V'(t) + c_i W'(t) \tag{10}$$

The auto correlation of the fluctuating Doppler frequency $F_i'(t)$ is

$$\begin{aligned}\frac{\lambda^2}{T}\int_0^T F_i'(t)\,F_i'(t+\tau)dt = {} & \lambda^2\,\overline{F_i'(t)\,F_i'(t+\tau)} = \\ & a_i^2\,\overline{U'(t)\,U'(t+\tau)} + b_i^2\,\overline{V'(t)\,V'(t+\tau)} + c_i^2\,\overline{W'(t)\,W'(t+\tau)} \\ & + a_i b_i\,\overline{U'(t)\,V'(t+\tau)} + a_i c_i\,\overline{W'(t)\,U'(t+\tau)} \\ & + a_i b_i\,\overline{V'(t)\,U'(t+\tau)} + b_i c_i\,\overline{V'(t)\,W'(t+\tau)} \\ & + a_i c_i\,\overline{U'(t)\,W'(t+\tau)} + b_i c_i\,\overline{W'(t)\,V'(t+\tau)}\end{aligned} \tag{11}$$

For $\tau = 0$, Eq. 11 becomes

$$\begin{aligned}\lambda^2\,\overline{F_i'(t)^2} = {} & a_i^2\,\overline{U'(t)^2} + b_i^2\,\overline{V'(t)^2} + c_i^2\,\overline{W'(t)^2} \\ & + 2a_i b_i\,\overline{U'(t)\,V'(t)} + 2\,a_i c_i\,\overline{U'(t)\,W'(t)} \\ & + 2b_i c_i\,\overline{V'(t)\,W'(t)}\end{aligned} \tag{12}$$

Equation 12 contains six unknowns, these being the variances and the mean instanstaneous cross products of the three velocity fluctuations. Thus in order to solve for the six unknowns, six independent measurements at six different geometrical configurations of the single LDV system would be required.

Equation 11 provides a relation from which the auto and cross correlation functions may be obtained. This equation contains nine unknowns for each time delay. Thus, for stationary data, all the correlations may be solved using nine independent equations obtained by conducting LDV measurements at nine independent geometrical configurations.

It can further be shown that the spectra of the individual time functions are related to the spectra of the correlation functions. Consider two functions and their respective Fourier representations

$$f(t) = \frac{a_o}{2} + \sum_{n=1}^{\infty} a_n \cos n \omega t + b_n \sin n \omega t \tag{13}$$

$$g(t) = \frac{c_o}{2} + \sum_{n=1}^{\infty} c_n \cos n \omega t + d_n \sin n \omega t \tag{14}$$

Where:

$$a_n = \frac{2}{T_1} \int_o^{T_1} f(t) \cos n \omega t \, dt \tag{15}$$

$$b_n = \frac{2}{T_1} \int_o^{T_1} f(t) \sin n \omega t \, dt \tag{16}$$

$$c_n = \frac{2}{T_1} \int_o^{T_1} g(t) \cos n \omega t \, dt \tag{17}$$

$$d_n = \frac{2}{T_1} \int_o^{T_1} g(t) \sin n \omega t \, dt \tag{18}$$

The cross correlation of f(t) and g(t) now becomes:

$$R_{fg}(\tau) = \overline{f(t)\ g(t + \tau)} = \frac{1}{T_1} \int_o^{T_1} f(t)\ g(t + \tau)\ dt \tag{19}$$

$$= \frac{a_c\ c_o}{4} + \sum_{n=1}^{\infty} \frac{a_n c_n + b_n d_n}{2} \cos n\omega\tau + \frac{a_n d_n - c_n b_n}{2} \sin n\omega\tau$$

When f(t) and g(t) are identical functions, the correlation is known as the auto correlation, and $a_n = b_n$ and $b_n = d_n$. Equation (19) becomes:

$$R_{ff}(\tau) = \overline{f(t)\ f(t+\tau)} = \frac{a_0{}^2}{4} + \sum_{n=1}^{\infty} \frac{a_n{}^2 + b_n{}^2}{2} \cos n\omega\tau \qquad (20)$$

Equations (19) and (20) are the Fourier transformation of the cross and auto correlations respectively. The spectral amplitude of the cross correlation function is directly related to the spectra of the individual functions. The absolute value of the spectra of the cross correlation is known as the cross power spectra of the functions f(t) and g(t). Also the spectral amplitudes of the auto correlation are the power spectral amplitudes of the original time function. Thus the power spectra and cross power spectra may be calculated from the auto and cross correlation functions.

SIMULTANEOUS EQUATIONS EVALUATIONS

Although the previous developments theoretically demonstrate that the single LDV system can provide a technique for obtaining both three dimensional mean and statistical flow information in a stationary flow field, the experimental feasibility of using the techniques needs to be examined. The basis of the described techniques, hinge on the solution of sets of independent linear equations containing either three, six or nine unknowns. In the solution of such sets of equations, small errors in the LDV measurements at any given geometrical system arrangement, can result in exceedingly large errors in the solution to the unknown values in the set of equations. In order to assess the magnitude of such errors, calculations were conducted for the three, six, and nine equations cases for possible geometrical arrangements of a typical reference-scatter type single LDV system.

Figure 2 shows a schematic of the geometrical instrument arrangement of a single component reference-scatter type LDV instrument. Note that the reference laser beam is along the Z axis. For this arrangement, the two variables which define an independent measurement are the angles Θ and α. The angle Θ defines the location of the plane formed by the reference and scatter beams with respect to the Y axis. The angle α is the scattering angle and is formed by the intersection of the reference and scatter beams.

In the calculations conducted for the 3, 6, and 9 equation cases, the LDV system was assumed to be at different scatter angles and the optical package, which collects the scattered light, was assumed to be rotated to different values of Θ. For example, in one of the calculations, α was assumed to be 12 degrees, while the instrument was rotated to Θ values of 0°, 120° and 240°.

The equations of interest in the calculations are:

<u>3 Equation Case for Mean Values</u>

$$\lambda\overline{F_i\ (t)} = a_i\ \overline{U(t)} + b_i\ \overline{V(t)} + c_i\ \overline{W(t)} \tag{5}$$

where $i = 1 \longrightarrow 3$

<u>6 Equation Case for RMS and Instanstaneous Cross Products</u>

$$\begin{aligned}\lambda^2\overline{F_i'(t)^2} &= a_i\ \overline{U'(t)^2} + b_i^2\ \overline{V'(t)^2} + c_i^2\ \overline{W'(t)^2} \\ &+ 2a_ib_i\ \overline{U'(t)V'(t)} + 2a_ic_i\ \overline{U'(t)W'(t)} \\ &+ 2b_ic_i\ \overline{V'(t)W'(t)}\end{aligned} \tag{12}$$

where $i = 1 \longrightarrow 6$

<u>9 Equation Case for Auto and Cross Correlations</u>

$$\begin{aligned}\lambda^2\overline{F_i'(t)\ F_i'(t+\tau)} &= a_i^2\ \overline{U'(t)U'(t+\tau)} + b_i^2\ \overline{V'(t)V'(t+\tau)} \\ &+ c_i^2\ \overline{W'(t)W'(t+\tau)} + a_ib_i\ \overline{U'(t)V'(t+\tau)} \\ &+ a_ic_i\ \overline{U'(t)W'(t+\tau)} + a_ib_i\ \overline{V'(t)U'(t+\tau)} \\ &+ b_ic_i\ \overline{V'(t)W'(t+\tau)} + a_ic_i\ \overline{W'(t)U'(t+\tau)} \\ &+ b_ic_i\ \overline{W'(t)V'(t+\tau)}\end{aligned} \tag{11}$$

where $i = 1 \longrightarrow 9$

For the laser system and arrangement shown in Fig. 2, the coefficients in the above equations are:

$a_i = -\sin\Theta_i \sin\alpha_i$

$b_i = \cos\Theta_i \sin\alpha_i$

$c_i = \cos\alpha_i - 1$

Also, for the LDV system considered, it was assumed that a frequency tracker was used to track the Doppler frequency. This instrument provides a DC voltage output $\overline{E_i(t)} \propto \overline{F_i(t)}$ and a AC voltage output $E_i'(t) \propto F_i'(t)$.

The constant of proportionality between the output voltage and input frequency may be written as

$$\overline{F_i(t)} = \frac{D}{\lambda} \overline{E_i(t)}$$

where D has dimensions of velocity per volt.

For the calculations made here, D was assumed to be either 3.90 (m/sec)/volt or 6.58 (m/sec)/volt, which represented a typical range of values which can be achieved with the frequency trackers described in Ref. 1.

In order to determine the sensitivity of a LDV geometrical arrangement for a given set of measurements, it is necessary to set-up the coefficients of the simultaneous equations which defines the configurations. For the three equation case, these equations may be written as

$$\begin{aligned}
\overline{E_1(t)} &= A_1 \overline{U(t)} + B_1 \overline{V(t)} + C_1 \overline{W(t)} \\
\overline{E_2(t)} &= A_2 \overline{U(t)} + B_2 \overline{V(t)} + C_2 \overline{W(t)} \\
\overline{E_3(t)} &= A_3 \overline{U(t)} + B_3 \overline{V(t)} + C_3 \overline{W(t)}
\end{aligned} \tag{21}$$

where $A = a_1/D$, $B_1 = b_1/D, \cdots$etc.

The sensitivity of the measurements of E_1, E_2, and E_3 to a determination of the three velocity components is obtained by simultaneously solving Eqs. 21 for the velocities in terms of the measured voltages. This can be written as

$$\begin{aligned}
\overline{U(t)} &= L_1 \overline{E_1(t)} + M_1 \overline{E_2(t)} + N_1 \overline{E_3(t)} \\
\overline{V(t)} &= L_2 \overline{E_1(t)} + M_2 \overline{E_2(t)} + N_2 \overline{E_3(t)} \\
\overline{W(t)} &= L_3 \overline{E_1(t)} + M_3 \overline{E_2(t)} + N_3 \overline{E_3(t)}
\end{aligned} \tag{22}$$

In Eq. 22 the sensitivity of the voltage measurement to a velocity component, i.e. ΔVelocity/ΔVoltage is given by the coefficients L_i, M_i, and N_i. These coefficients are obtained by inverting the matrix formed by the coefficients in Eq. 21.

By using typical values of A_i, B_i, C_i in Eq. 21 for different geometrical arrangements of the LDV instrument, values of L_i, M_i, and N_i were obtained. The geometrical values used in determining A_i, B_i, and C_i along with the values of the matrix inversion are given in Table I. This table gives the geometrical arrangement of the cases considered which gave the best values of L_i, M_i, and N_i and the geometrical arrangement which gave the worst values. The best case was defined to be the geometrical arrangement which gave the lowests values for the output coefficients L_i, M_i, and N_i, and the worst case was defined to be the geometrical arrangement which gave the highest values for the output coefficients. The significance of the two cases can best be seen by noting that in the best case the output coefficients are of the order 10^1 while the output coefficients are of the order from 10^2 to 10^5 for the worst case. From a measurement standpoint this means that a voltage measurement of $\pm 1 \times 10^{-3}$ volts in the best case, will correspond to a velocity measurement of $\pm 1 \times 10^{-2}$ m/ft and for the worst case to $\pm 1 \times 10^{0}$ to $\pm 1 \times 10^{2}$ m/sec. Thus, it can be seen that measurements conducted using the geometrical arrangement of the worst case will impose a severe restriction on the precision a voltage measurement must be made in order to obtain an accurate velocity measurement.

After examining the results of the different cases that were considered for the 3 equation case the following trends were noted.

1. Better accuracy is achieved when α is increased.
2. Better accuracy is achieved when the three measurements are conducted at 120° intervals of Θ.
3. Better accuracy is achieved as the value of D is reduced.

The six and nine equations which defined the different statistical quantities were also examined for different geometrical arrangements of a single component reference scatter LDV system. Using the equations given by

3. The auto and cross correlations for a three dimensional flow can be measured using nine independent measurements.

The defining equations were examined for a single component forward scatter LDV system for different geometrical arrangements. It was found for the arrangements considered;

1. that the three mean velocities could be determined with a reasonable accuracy and
2. that the higher moment statistical quantities would be very difficult to determine accurately.

Only a limited number of geometrical arrangements of a particular LDV system were considered here. Any geometrical arrangement considered should always be guided by the physical constraints imposed by the LDV system and the flow facility, since many arrangements that are theoretically possible are not physically practical.

It should be noted that reducing the flow field to a two dimensional case causes the required number of independent configurations to be noticeably reduced for the determination of any particular statistical quantity. That is only two configurations are needed for mean measurements, three for RMS and the cross product, and four independent observations to reduce all time correlations. It is of further interest to note that if the LDV signals are collected from three independent directions simultaneously (Ref. 2), the three demensional statistical quantities may be obtained directly with a minimum restriction on the precision with which the Doppler frequencies must be detected.

(10) and (11) the matrix of the coefficients were inverted to obtain the output coefficients which related the voltage measurement to the different statistical velocity parameters. This investigation indicated that the output coefficients for the 6 equation case were of the order 10^{-3} to 10^{12} (m/sec)/volt and for the 9 equation case of the order 10^{1} to 10^{11} (m/sec)/volt. The magnitude of the output coefficients would require a extremely precise voltage measurement capability in order to obtain a satisfactory accuracy in the measurement of the statistical velocity parameters. Tables II and III provide a tabulation of geometrical arrangements considered for the 6 and 9 equation cases and the magnitudes of the output coefficients.

CONCLUSIONS

The general equations defining the three dimensional mean and fluctuating velocity components measured by a single LDV instrument were presented. It was shown that mathematically, a single component LDV system has the ability to measure both three dimensional mean and fluctuating velocity components assuming that the flow field is stationary. In particular, it was found that:

1. The three component mean velocities can be measured by conducting LDV measurements at three independent geometrical configurations of a LDV system.
2. The RMS and instantaneous cross product averages for a three dimensional flow can be measured by making LDV measurements at six independent geometrical configuration.

REFERENCES

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Table 1
Results of Solution for
Three Independent LDV Equations

Best Case Considered: D = 12.8(ft/sec/volt)

$\alpha_1 = \alpha_2 = \alpha_3 = 28°$

$\theta_1 = 0°,\ \theta_2 = 120°,\ \theta_3 = 240°$

Input Coefficients (volts/(ft/sec)

$A_1 = 0.0$	$B_1 = 3.643 \times 10^{-2}$	$C = -9.084 \times 10^{-3}$
$A_2 = -3.155 \times 10^{-2}$	$B_2 = -1.821 \times 10^{-2}$	$C = -9.084 \times 10^{-3}$
$A_3 = 3.155 \times 10^{-2}$	$B_3 = -1.821 \times 10^{-2}$	$C_3 = -9.084 \times 10^{-3}$

Output Coefficients ((ft/sec)/volt)

$L_1 = -5.769 \times 10^{-4}$	$M_1 = -1.584 \times 10^{1}$	$N_1 = 1.584 \times 10^{1}$
$L_2 = 1.829 \times 10^{1}$	$M_2 = -9.148 \times 10^{0}$	$N_2 = -9.158 \times 10^{0}$
$L_3 = -3.669 \times 10^{1}$	$M_3 = -3.669 \times 10^{1}$	$N_3 = -3.669 \times 10^{1}$

Worst Case Considered: D = 21.6((ft/sec)/volt)

$\alpha_1 = \alpha_2 = \alpha_3 = 5°$

$\theta_1 = 270°,\ \theta_2 = 280°,\ \theta_3 = 290°$

Input Coefficients (volts/(ft/sec))

$A_1 = 4.027 \times 10^{-3}$	$B_1 = 2.165 \times 10^{-8}$	$C_1 = -1.758 \times 10^{-4}$
$A_2 = 3.966 \times 10^{-3}$	$B_2 = 6.993 \times 10^{-4}$	$C_2 = -1.758 \times 10^{-4}$
$A_3 = 3.784 \times 10^{-3}$	$B_3 = 1.377 \times 10^{-3}$	$C_3 = -1.758 \times 10^{-4}$

Output Coefficients ((ft/sec)/volt)

$L_1 = -7.923 \times 10^{3}$	$M_1 = 1.609 \times 10^{4}$	$N_1 = -8.172 \times 10^{3}$
$L_2 = -2.123 \times 10^{3}$	$M_2 = 2.838 \times 10^{3}$	$N_2 = -7.150 \times 10^{2}$
$L_3 = -1.871 \times 10^{5}$	$M_3 = 3.686 \times 10^{5}$	$N_3 = -1.871 \times 10^{5}$

Table II

Geometrical Arrangements Considered for Solution to Six LDV Equations Defining the Three Dimensional RMS and Cross Product Terms.

α*	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	Output Coeff. Magnitude (ft/sec)/volt))
5	0	45	90	135	270	315	10^{-1}-10^{12}
8	0	45	90	135	270	315	10^{-1}-10^{11}
9	0	45	90	135	270	315	10^{-2}-10^{12}
10	0	45	90	135	270	315	10^{-2}-10^{12}
11	0	45	90	135	270	315	10^{3}-10^{16}
12	0	45	90	135	270	315	0-10^{16}
5	0	60	120	180	240	300	10^{-3}-10^{12}
12	0	60	120	180	240	300	10^{-3}-10^{11}
5	270	280	290	300	310	320	10^{6}-10^{13}
12	270	280	290	300	310	320	10^{4}-10^{11}
5	270	285	300	315	330	345	10^{5}-10^{12}
8	270	285	300	315	330	345	10^{4}-10^{11}
11	270	285	300	315	330	345	10^{5}-10^{12}
12	270	285	300	315	330	345	10^{4}-10^{11}

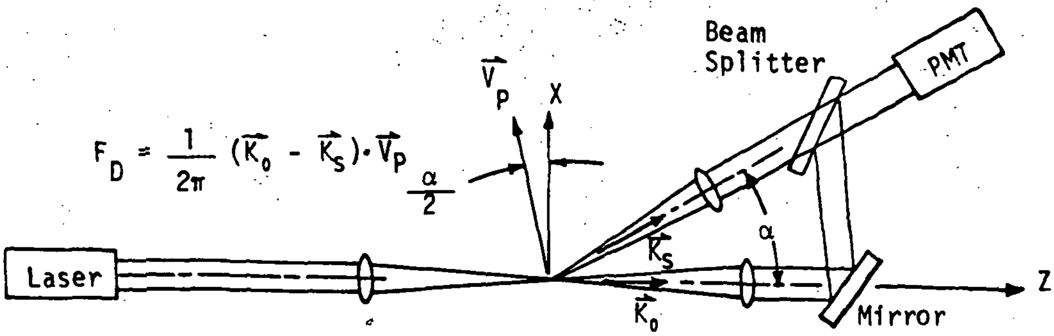
* All angles in degrees

Table III

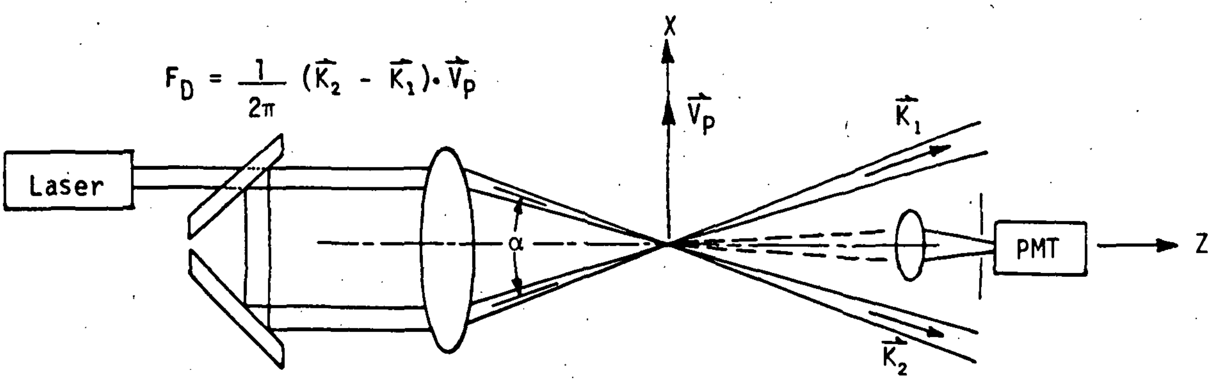
Geometrical Arrangements Considered for Solution to the Nine LDV Equations Defining the Three Dimensional Auto and Cross Correlations

α*	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	Output Coeff. Magnitude (ft/sec)/volt))
5	0	30	60	90	120	150	240	270	300	10^3-10^{12}
8	0	30	60	90	120	150	240	270	300	10^3-10^{11}
9	0	30	60	90	120	150	240	270	300	10^3-10^{11}
10	0	30	60	90	120	150	240	270	300	10^4-10^{11}
11	0	30	60	90	120	150	240	270	300	10^4-10^{11}
12	0	30	6	90	120	150	240	270	300	10^4-10^{12}
5	0	40	80	120	160	200	240	280	360	10^3-10^{12}
12	0	40	80	120	160	200	240	280	360	10^3-10^{12}
5	270	280	290	300	310	320	330	340	350	10^4-10^{12}
8	270	280	290	300	310	320	330	340	350	10^4-10^{11}
12	270	280	290	300	310	320	330	340	350	10^2-10^{11}
45	270	280	290	300	310	320	330	340	350	10^2-10^8
90	315	325	335	345	355	5	15	25	35	10^3-10^7

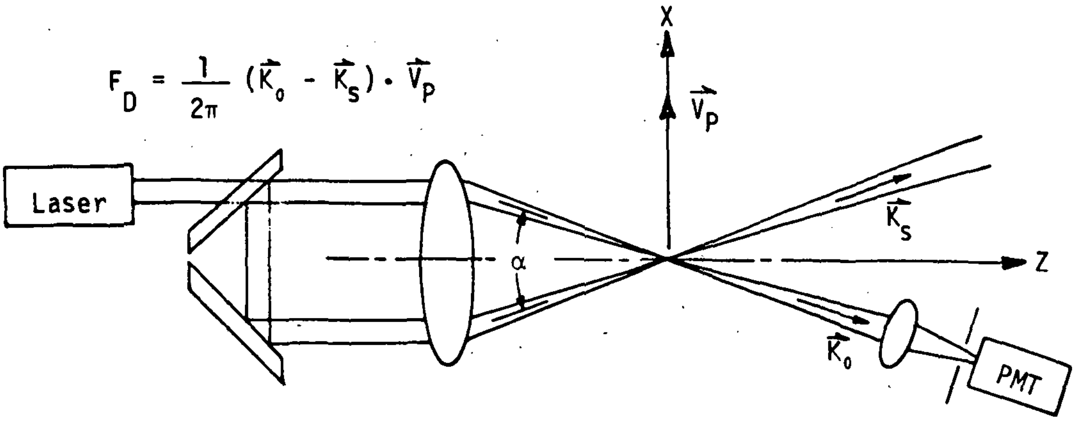
* All angles in degrees



Reference - Forward Scatter System



Dual Beam Forward Scatter System



Dual Beam Reference Scatter System

FIGURE 1. SCHEMATIC OF DIFFERENT LDV SYSTEM ARRANGEMENTS

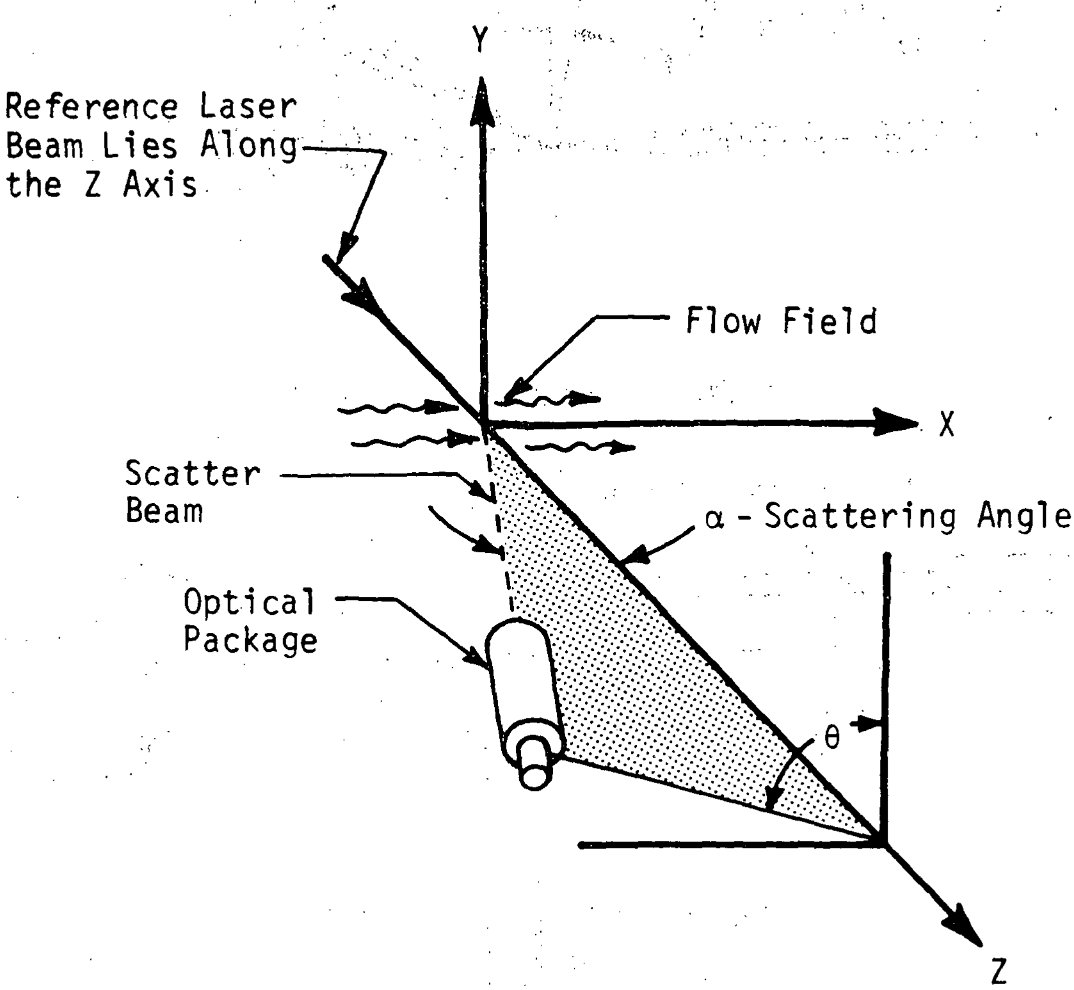


FIGURE 2. SCHEMATIC OF A TYPICAL ANGULAR ARRANGEMENT OF A SINGLE-REFERENCE-SCATTER LDV SYSTEM

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By

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This document has also been reviewed and approved for technical accuracy.

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