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# LASER AND ACOUSTIC DOPPLER TECHNIQUES FOR THE MEASUREMENT OF FLUID VELOCITIES


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*Marshall Space Flight Center, Alabama*

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**16. ABSTRACT**

An overview of current laser and acoustic Doppler techniques is presented. Results obtained by Doppler anemometry and conventional sensors are compared. Comparisons include simultaneous velocity measurements by hot wire and a three-dimensional laser anemometer made in a gaseous pipe flow as well as direct comparisons of atmospheric velocities measured with propeller and cup anemometry. Scanning techniques are also discussed. Conclusions and recommendations for future work are presented.

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# LASER AND ACOUSTIC DOPPLER TECHNIQUES FOR THE MEASUREMENT OF FLUID VELOCITIES

## I. INTRODUCTION

In recent years there has been considerable emphasis placed on developing techniques to remotely measure the velocity of confined and free fluid flows (such as atmospheric, oceanic, wind tunnel, blood, pipe, and channel flows, etc.). The laser Doppler and acoustic Doppler are two techniques which will be examined in this paper. Both techniques are based on the Doppler effect. The Doppler effect is the fact that there is a change in frequency with which energy reaches a receiver when the receiver and the energy source are in motion relative to one another. In the cases of the laser and acoustic Doppler systems, energy is transmitted to a moving scatterer (tracer) which then becomes a source and the energy is transmitted to a receiver. Major efforts in the development of the laser and acoustic Doppler systems have been under way since the 1960's [1,2,3]. It is the intent of this paper to skip the developmental years of these systems and present the techniques which are presently employed and the results which they are obtaining.

## II. BACKGROUND AND BASIC PRINCIPALS

The technique of using Doppler anemometry is based on the fact that radiation, acoustical or electromagnetic (laser), passing through a fluid is scattered by tracers in the fluid. (In the case of laser Doppler systems the scattering occurs due to particles suspended in the fluid. In the case of acoustical Doppler, the scattering may occur due to temperature or velocity gradients.) The scattered radiation contains information on the velocity of the tracers from which the radiation was scattered.

The information on the velocity of the tracer manifests itself by frequency shifting the radiation striking the tracer. The amount that the source frequency is shifted, $\Delta f$, upon striking the tracer and returning to a receiver is called the Doppler shift or Doppler frequency and is expressed mathematically as:

$$\Delta f = \frac{\overline{V}}{\lambda} \cdot (\overline{e}_s - \overline{e}_i) \qquad (1)$$

where $\overline{V}$ is the velocity vector of the tracer, $\lambda$ is the wavelength or the source radiation, $\overline{e}_s$ is a unit vector along the scattered radiation (a unit vector from the scattering source to the receiver), and $e_i$ is a unit vector along the incident radiation (a unit vector from the source to the tracer).

From Eq. 1 it is noted that a single Doppler system gives a one-dimensional velocity measurement and the velocity component measured lies along a vector bisecting the angle betwee- the incident and scattered radiation. Figure 1 presents a three-dimensional view of a single radiation Doppler system. In the Figure 1 case the axes are oriented such that the velocity component sensed by the system lies along the z axes. Thus, any motion in the x-y plane would not be detected by the Doppler system. The use of additional Doppler systems would allow 2 or 3 dimensional velocity measurements, however.

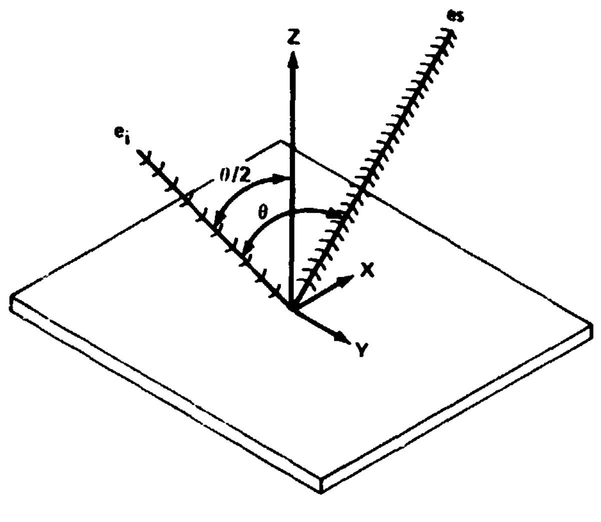


FIGURE 1. A THREE-DIMENSIONAL VIEW OF A SINGLE RADIATION DOPPLER SYSTEM NOTE: THE PLANE FORMED BY THE LINES OF THE INCIDENT RADIATION AND SCATTERED RADIATION IS NORMAL TO THE x-y PLANE.

Figure 2 presents a plane view of a single Doppler system. Here, again, it is noted that the velocity sensed is parallel to the bisector of the incident and scattered radiation. In terms of the angles given in Figure 2, Eq. 1 may be written:

$$\Delta f = \frac{(\overline{V} \cos \beta)}{\lambda} \left(2 \sin \frac{\theta}{2}\right) \tag{2}$$

where β is the angle between the total velocity vector and the bisector of the incident and scattered radiation and θ is the angle between the incident and scattered radiation.

In terms of the velocity measured, $V_m$, Eq. 2 may be written:

$$V_m = \overline{V} \cos \beta = \frac{\Delta f \lambda}{2 \sin \theta/2} . \tag{3}$$

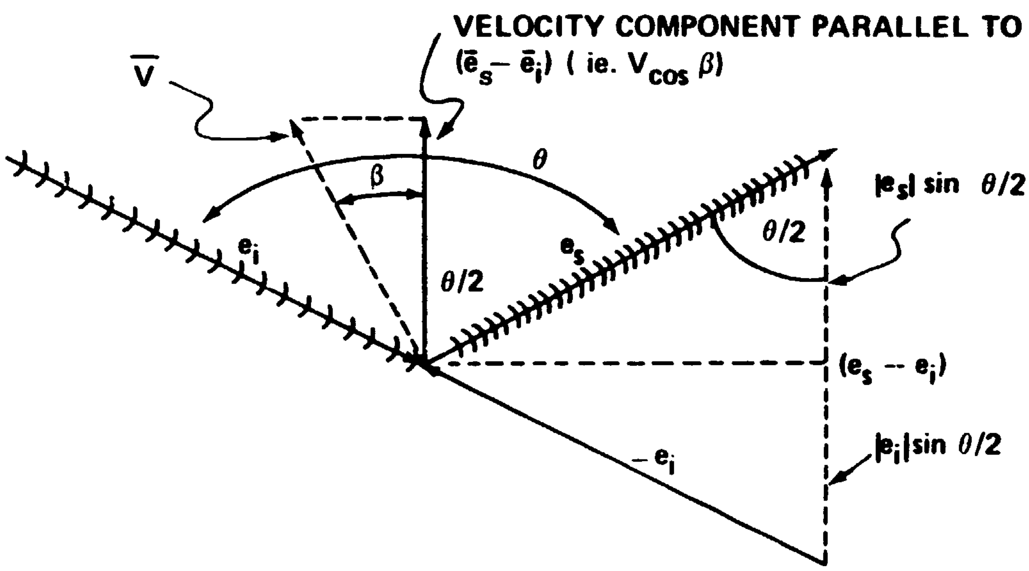


FIGURE 2. PLANE VIEW OF A SINGLE RADIATION DOPPLER SYSTEM NOTE: ONLY THE COMPONENT OF VELOCITY PARALLEL TO $(\overline{e}_s - \overline{e}_i)$ IS DETECTED.

If one measures pure backscatter (i. e., the scattered radiation is measured along the same paths as the radiation was sent out, θ = 180°), Eq. 3 becomes

$$V_m = \frac{\Delta f \lambda}{2}, \text{ (for } \theta = 180^\circ) \quad . \tag{4}$$

Eqs. 1 through 4 give the basic equations for a single Doppler system. As will be shown later, the use of three separate Doppler signals can give the investigator a means to directly measure the three dimensional flow field.

## III. LASER DOPPLER

The laser Doppler, generally referred to as a laser Doppler velocimeter (LDV), measures the Doppler frequency shift in laser light caused by moving particles scattering the light. This frequency shift is related to the wavelength of the light, the geometrical direction of the scattered light, and the velocity of the particles producing the shift. Eqs. 1 through 4 give the Doppler frequency as a function of wavelength, direction, and velocity of the tracer. For a particular test configuration the laser wavelength and geometrical scattering direction are given. Knowing the laser wavelength and test geometry, the measuring of the Doppler frequency shift allows the calculation of the scattering sources velocity. In this case the scattering source is generally particles imbedded within the flow. The particle velocity is then related to the fluid flow in which the particle is suspended. If the particle is very small, it is generally considered to move directly with the fluid surrounding the particle.

In general a measurable Doppler frequency is obtained by either (1) mixing the scattered laser light with some of the local oscillator (original laser) light on a photodetector or (2) splitting the original laser beam and making the dual beams cross, setting up a fringe pattern in space and sensing particle scattering that comes from the fringe pattern on a photodetector. The system which mixes (or beats) the scattered light with some of the local oscillator (LO) light on a photodetector is called a reference beam or local oscillator system. Figure 3a shows a forward scatter reference beam system [4]. Note that both the local oscillator (laser beam) and receiver optics are focused such that only scattering from the focal volume is sensed on the photodetector. In the case of Figure 3a the photodetector is shown as a photomultiplier (PMT).

In the reference beam system the mixing (or beating) of the scattered light and LO occurs on the photodetector. The mixing of two waves of different frequencies produces a function of the sum and difference of the two frequencies. Only the

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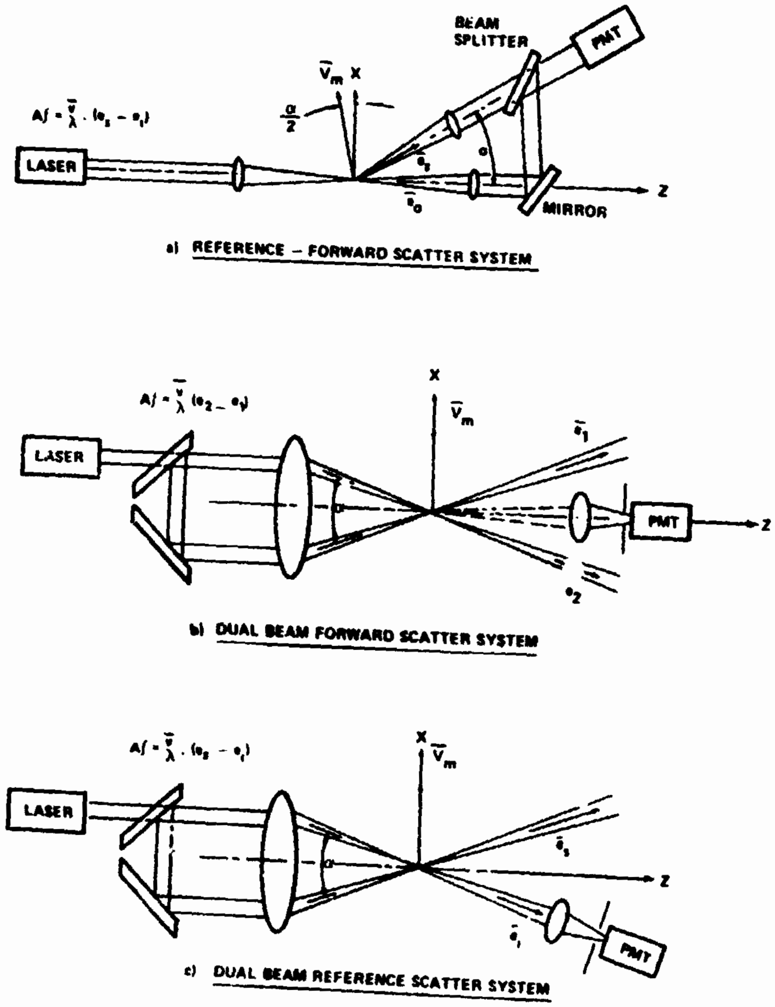


FIGURE 3. SCHEMATIC OF DIFFERENT LDV SYSTEM ARRANGEMENTS

frequency difference is low enough to be detected by the photodetector. This frequency difference is known as the Doppler frequency and is detected by the photodetector due to an apparent fringe pattern moving across the detector, that is the detector area is impacted by radiation whose amplitude is driven by the Doppler frequency.

In the dual beam system the original laser beam is split, separated, and then both beams are focused so as to cross at some point in space. Where the beams cross, a fringe pattern is established which a particle encounters as it passes through the focal volume.

As the particle passes through the fringe pattern, the intensity of the scattering is dictated by whatever portion of the fringe pattern the particle is in. Figure 3b gives a schematic of a forward scatter fringe system. The receiver optics in the dual beam system are focused on the volume where the two beams cross. Figure 3c is a schematic of a dual beam reference system which is a combination of the dual beam and reference beam systems.

In these first examples, we have beat two signals together to produce a difference frequency which was related to particle velocity. It should be pointed out that if the signals are beat together, as described to this point, an ambiguity in direction of 180° is present, that is, the difference in frequency of the scattered radiation and original laser radiation would be the same whether the particle was moving in a given direction or moving in a direction that was exactly opposite (180°). This direction ambiguity can be corrected, however, by frequency shifting the LO (original laser source light). Frequency shifting (or translating) the LO causes a particle with no velocity to produce a difference (Doppler) frequency equal to the amount that the LO was shifted. Figure 4 gives a schematic to show the effect of frequency translation of the original laser light. The frequency translation may be accomplished by several methods such as scattering the LO (original laser light) off a target moving at a constant rate or shifting the LO by means of an acousto-optical translator. The latter appears to be the superior method. In the acousto-optical method, the LO is passed through a crystal or liquid which is acoustically excited. Part of the LO is shifted by some angle $\delta$ and translated in frequency. The most common of these systems is called a Bragg cell and is in many of the small commercial laser Doppler systems. These systems operate in the visible spectrum and generally employ a helium-neon laser with a $0.6328\mu$ wavelength. Presently Marshall Space Flight Center is having translators developed for their infrared laser Doppler systems

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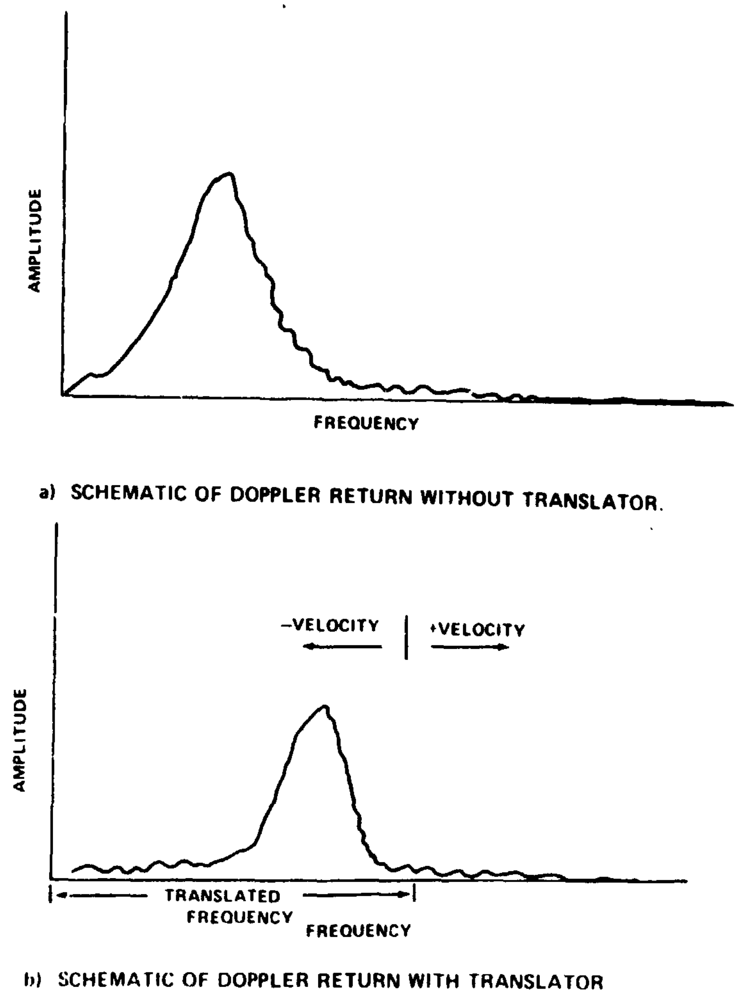



FIGURE 4. SCHEMATIC OF DOPPLER RETURN WITH AND WITHOUT FREQUENCY TRANSLATOR

(10.6μ wavelength). The reason one uses a translator rather than actually measuring the light frequencies is that the frequencies are extremely large. For example take the Argon laser, a common laser used in laser Doppler research, whose strongest line is at 0.5145μ ($0.5145 \times 10^{-6}$ m). The frequency one would measure is equal to the speed of light divided by the wavelength; that is, (299,860,000 m/sec)/($0.5145 \times 10^{-6}$ m) = $5.828 \times 10^{14}$Hz, which would be difficult to measure with the accuracy needed to define the flow measurement. The measured Doppler shift for a backscatter measurement, Eq. 4, for a measured velocity of 1 meter/sec would be: $\Delta f = \frac{2Vm}{\lambda} = \frac{(2)1\ m/sec}{(0.5145 \times 10^{6} m)} = 3.89 \times 10^{6}$Hz. Therefore, the measurement accuracy would have to be $\Delta f/f = 6.67 \times 10^{-9}$.

Another difficulty could arise in that the laser wavelength could change slightly with time. Thus, the beating technique is considered to be the most practical at the present time. Another difficulty that is common to most laser systems is that the distance traveled between the LO beam and the scattered light must be within the coherence limits of the laser. That is, light which is emitted and then mixed with light which was emitted at a time such that the difference in the path lengths is greater than the coherence length of the laser may not beat properly. The coherence length for a helium-neon laser may be 20 cm to several kilometers [5]; the coherence length of an argon laser is about 10 cm (which may be increased to 10 meters using an etalon) while a $CO_2$ laser's coherence length may be several kilometers. An etalon is an optical device which is generally placed in the laser cavity to better select the polarization and wavelength that the cavity amplifies and emits.

The detector in the local oscillator case has the scattered radiation and the local oscillator radiation impacting on its surface simultaneously. If the radiation from the local oscillator is given by $\sin 2\pi f_o t$, the scattered radiation could be given by $\sin [2\pi f_o t + 2\pi \Delta f_o t + \phi]$. The current output from the photodetector, $i_D$, is proportional to the square of the incident radiation. That is:

$$i_D \propto \left\{ \sin 2\pi f_o t + \sin (2\pi f_o t + 2\pi \Delta f_o t + \phi) \right\}^2$$

$$= 4 \sin^2 \left( \frac{4\pi f_o t + 2\pi \Delta f_o t + \phi}{2} \right) \sin^2 \left( \frac{2\pi \Delta f_o t + \phi}{2} \right). \quad (5)$$

NOTE: $\sin^2 \alpha = \frac{1 - \cos^2 \alpha}{2}$ .

However, $2\pi f_o$ is a light frequency too high to be followed by the detector; thus only the mean value of the first term on the right is seen by the detector and Eq. 5 is reduced to:

$$i_D \propto 1 - \cos(2\pi\Delta f_o t + \phi). \qquad (6)$$

Thus the only frequency sensed by the detector is $\Delta f_o$, which is the difference or Doppler frequency.

## A. GENERAL TYPES OF LASER DOPPLER SYSTEMS

Brief descriptions of two configurations, local oscillator (reference beam) and dual beam, were presented earlier. These descriptions and uses will be expanded upon individually along with the scanning schemes presently employed.

### 1. Local Oscillator Focused Forward Scatter (CW) LDV Systems

Figure 3a gives a schematic of the local oscillator (reference beam) focused forward scatter LDV system. Figure 5 gives another view of a forward scatter reference system. From Eq. 1 it can be seen that the LDV systems are linear functions of frequency. From this it may be shown that for a statistically stationary flow a single LDV system may be used to obtain two or three dimensional information [4].

The method employed to get two- and three-dimensional information from a single LDV system is that statistical averages are made from several independent receiver locations at different times. Reference 4 shows that 3 independent measurements need to be taken to obtain three dimensional mean information, six would be necessary to obtain all mean instantaneous cross products (such as $\overline{U'V'}$ and $\overline{U'^2}$ where U' and V' are the velocity fluctuations in the x and y directions, respectively) and 9 independent correlation measurements would be necessary for correlation calculations. The method used is simply that the Doppler frequency may be written as a linear function of the three velocity components; i.e.,

$$\lambda \Delta f = a_1 V(t) + b_1 V(t) + c_1 W(t) \qquad (7)$$

where $\lambda$ is the wavelength of the laser, $\Delta f$ the Doppler frequency, $a_1$, $b_1$, and $c_1$ are constants determined by the geometrical configuration, and V(t), V(t) and W(t) are the instantaneous velocity

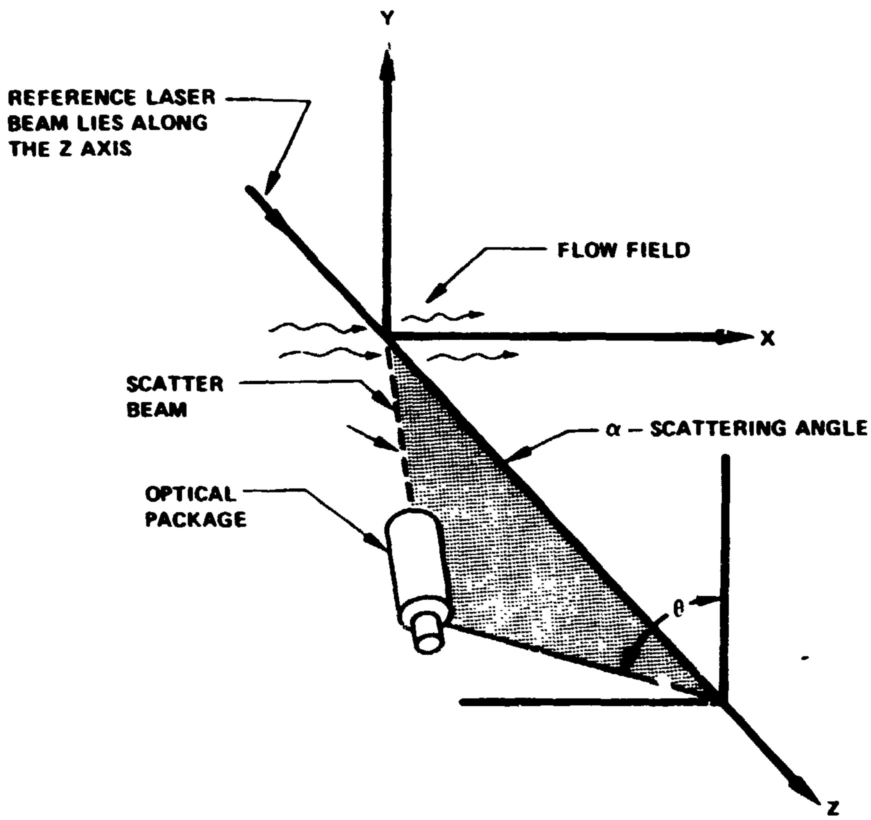



FIGURE 5. SCHEMATIC OF TYPICAL ANGULAR ARRANGEMENT OF A SINGLE REFERENCE LDV SYSTEM

components in the x, y, and z directions, respectively. Thus in a statistically stationary flow one could make three separate mean measurements with the receiver at three independent locations, which would give the experimenter three equations with three unknowns. The three unknowns in this case are $\overline{U}$, $\overline{V}$, and $\overline{W}$, the mean velocity components in the x, y, and z directions, respectively. Higher order velocity moments would require a greater number of independent observations as noted above. The experimenter must be careful, however, in that the larger the number of equations needed, the greater the precision of the measurements needed. Figure 6 is a schematic showing a cause of inaccuracy in LDV systems. It is shown that the angle sensed is never a line but some small angle, $d\gamma$, which means that the sensed direction is not really a line

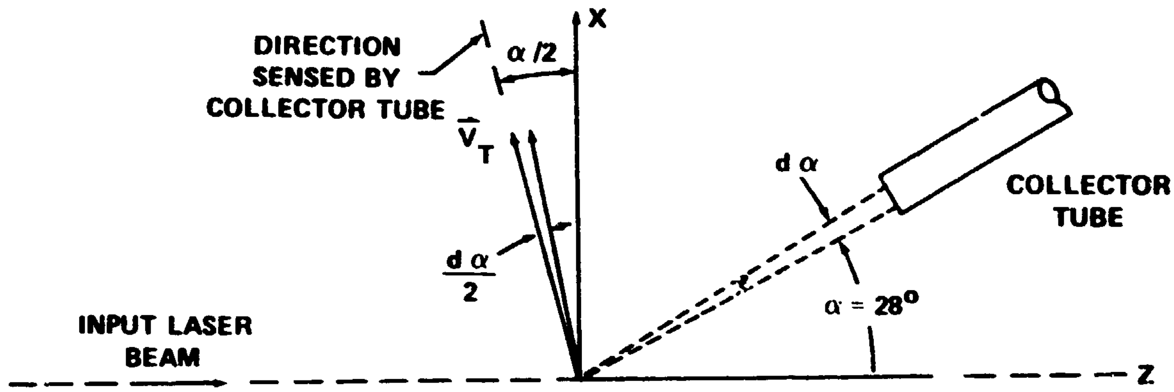
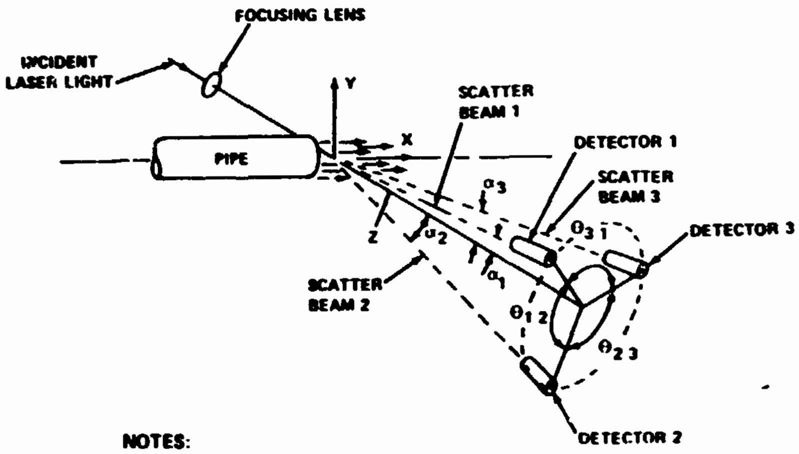



FIGURE 6. ANGULAR ACCURACY LIMITATIONS IN A LDV SYSTEM

but some small cone with a central angle of $\frac{d\gamma}{2}$. This angular error is related to what is called a Doppler ambiguity caused by finite transit time [6]. George and Lumley [6] also point out that other errors which arise in measuring with Doppler systems are mean velocity gradients and turbulent velocity gradients across the scattering volume along with normal electronic noise. It should be pointed out that any system with a finite sensing volume is subject to errors resulting from gradients across the sensing volume, from fluctuations smaller than the sensing volume and from electronic noise. These types of errors can become significant if one attempts to carry the accuracy of the measurement too far, such as could be the case in trying to define all second moment correlations of a three-dimensional flow field with a single LDV. As noted above, this would require nine independent measurements.

One of the best scanning techniques for a single LDV system is to simply set the optics for a particular range and then move the entire LDV system which, in turn, moves the sensing location.

In order to measure two-or three-dimensional flows, the author suggests that two or three receivers be employed simultaneously. Figure 7 is a schematic of a three-dimensional LDV




NOTES:

1. THE INCIDENT LASER BEAM IS IN THE XZ PLANE AND AT RIGHT ANGLES TO THE PIPE CENTERLINE.
2. THE VELOCITY COMPONENTS U, V, AND W ARE IN THE DIRECTIONS X, Y, AND Z RESPECTIVELY.
3. DETECTOR 3 IS IN THE X–Z PLANE.

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FIGURE 7. SCHEMATIC OF A THREE-DIMENSIONAL LDV AND ITS ALIGNMENT RELATIVE TO A PIPE FLOW

system which was used at Marshall Space Flight Center [7]. Note that three non-coplaner receivers are employed simultaneously. The Doppler output from each detector may be written as a linear function of U(t), V(t) and W(t), thus directly giving three equations with three unknowns which may be solved on line giving U(t), V(t), and W(t) directly [8]. If $\Delta f_1(t)$, $\Delta f_2(t)$, and $\Delta f_3(t)$ are the Doppler frequencies sensed at detector 1, detector 2, and detector 3 at time t, the U(t), V(t) and W(t) components can be written as:

$$
\begin{aligned}
U(t) &= A_1\,\Delta f_1(t) + A_2\,\Delta f_2(t) + A_3\,\Delta f_3(t) \\
V(t) &= B_1\,\Delta f_1(t) + B_2\,\Delta f_2(t) + B_3\,\Delta f_3(t) \qquad (7) \\
W(t) &= C_1\,\Delta f_1(t) + C_2\,\Delta f_2(t) + C_3\,\Delta f_3(t)
\end{aligned}
$$

where $A_i$, $B_i$, and $C_i$ relate the velocity components to the respective Doppler shifts. Figure 8 shows a schematic of the electronic network for reducing the Doppler signals to the U, V, and W components along with comparing the U component of the LDV system with the U component measured with a hot wire

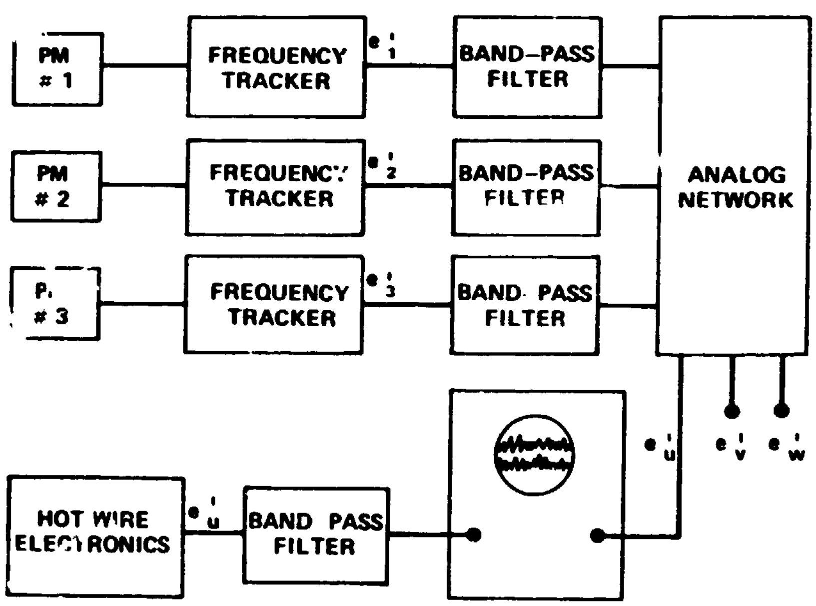


FIGURE 8. SCHEMATIC DIAGRAM OF ELECTRONIC NETWORK FOR COMPARING THE LDV AND HOT WIRE SIGNALS (NOTE: $e_i$ IS A VOLTAGE REPRESENTING THE $i^{th}$ QUANTITY.)

anemometer. Figure 9 shows an oscilloscope trace comparing the U component measured by a hot wire and the U component measured with the 3-D LDV system described above. The laser

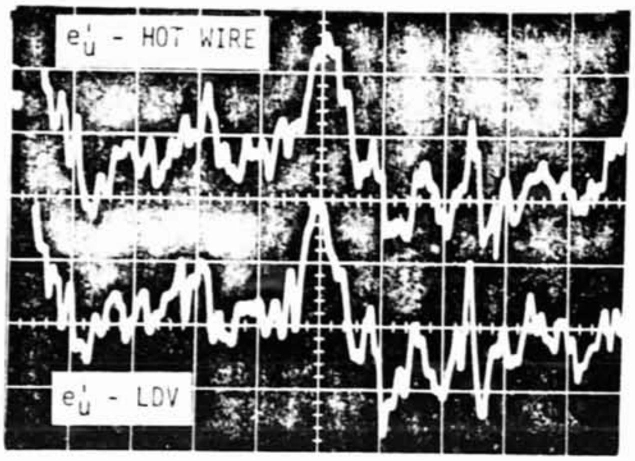


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FIGURE 9. COMPARISON OF U COMPONENT MEASURED BY AN LDV SYSTEM AND A HOT WIRE (NOTE: $e'_U$ IS THE VOLTAGE REPRESENTING THE U COMPONENT OF VELOCITY.)

used in the above tests was an argon laser emitting at the 0.5145μ wavelength.

The flow measured was at the exit of a fully developed pipe. The scanning technique employed was to crank the entire LDV system thus moving the focal (sensing) volume to a desired location. The results of the test are presented in Reference 7. The results indicate excellent agreement when compared to conventional systems. The advantage that the 3-D LDV system has over conventional systems is that the experimenter obtains on-line the 3-dimensional velocity field at the focal volume. The focal volume in the above experiment was found to be about 0.08 mm in diameter and about 0.27 mm long [7]. These dimensions are near those found in conventional hot wire anemometry. Figure 10 is an on-line 3-dimensional velocity display simultaneously with a hot wire output. The hot wire was placed at approximately 1 mm downstream from the sensing volume of the laser system.

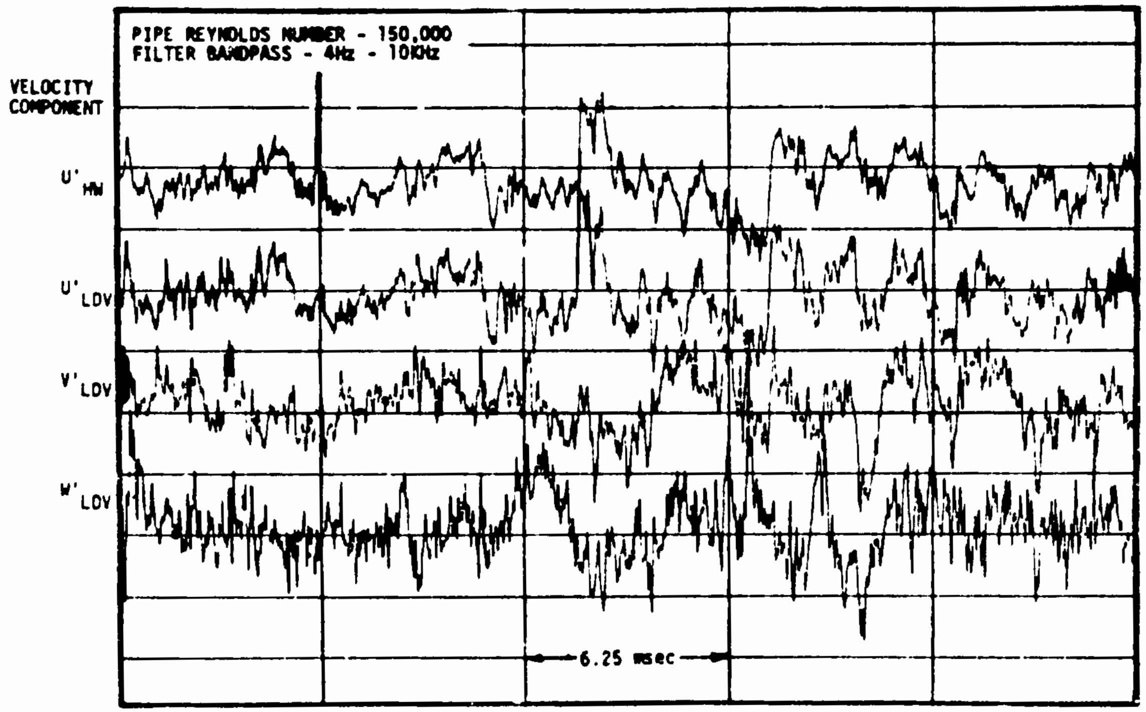



FIGURE 10. SIMULTANEOUS COMPARISON OF HOT WIRE AND LDV TURBULENT FLUCTUATIONS AT THE CENTER OF A TURBULENT PIPE FLOW

## 2. Local Oscillator for Focused Backscatter (CW) LDV Systems

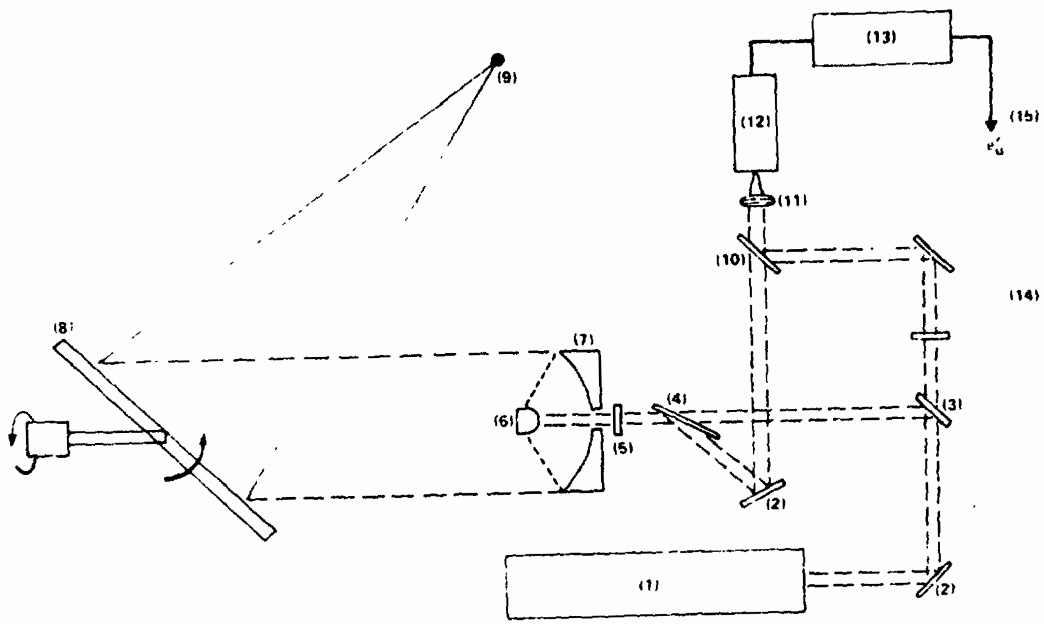
The formula for the Doppler frequency shift for the backscatter mode is given by Eqs. 1 through 4. For the case where the receiver is separated from the source (bistatic), the exact same approaches may be used as were employed with the forward scatter local oscillator. It should be noted, however, that in many cases the size of particle tracers scattering the light is of the same order of magnitude as the wavelength of light or larger. When the above is the case, the scattering is termed Mie scattering and the scattered intensity from the particle is very much dependent on angle and is the most intense in the forward direction. The ratio of the intensity of forward scatter to backscatter (with the same angle from the line of incident radiation) may be two orders of magnitude. Since the techniques employed for measuring the Doppler signal are the same for the forward bistatic and backscatter bistatic, this section will concern itself with systems employing co-axial (monostatic) backscatter (i.e., the receiver and source optics are the same). In the co-axial backscatter mode the Doppler shift is defined by Eq. 4. There are several advantages to using a co-axial (monostatic) focused backscatter system. Some of these are: (1) the same optics are used for focusing the transmitted and received radiation; (2) since the same optics are used for transmitting and receiving, there is no need to align two beams to cross in space (dual-beam system) nor to align the receiver focal volume with the LO focal volume (bistatic LO); (3) the Doppler shift comes from the component of velocity along the axis of the beam and thus there is no angular dependence of the Doppler shift.

Some disadvantages of the co-axial LDV system are: (1) spacial resolution is poorer than in the bistatic case and (2) more sophistication in optics is generally required. Figure 11 is a schematic of a co-axial focused backscatter LDV system with scanning capabilities which will be explored later.

Figure 12 gives the comparison of the resolution of co-axial, bistatic, and pulsed $CO_2$ LDV systems.

Because of the long coherence length of the $CO_2$ laser, it has been used in the development of co-axial LDV systems for measuring atmospheric flows [9,10].

Figure 13 and 14 show on-line comparisons of atmospheric velocities by a $CO_2$ co-axial LDV system and propeller anemometer at ranges of 60 meters and 200 meters. It should be noted




(1) $CO_2$ LASER
(2) FIRST SURFACE MIRROR
(3) Ge BEAMSPLITTER
(4) Ge BREWSTER WINDOW
(5) QUARTER WAVE PLATE
(6) SECONDARY MIRROR
(7) PRIMARY MIRROR
(8) BEAM DIRECTING MIRROR
(9) FOCAL VOLUME
(10) RECOMBINING Ge BEAMSPLITTER
(11) COLLECTING LENSE
(12) DETECTOR
(13) TRACKER
(14) Ge HALFWAVE PLATE
(15) VOLTAGE OUT REPRESENTING AXIAL VELOCITY

FIGURE 11. CO-AXIAL LASER DOPPLER SYSTEM

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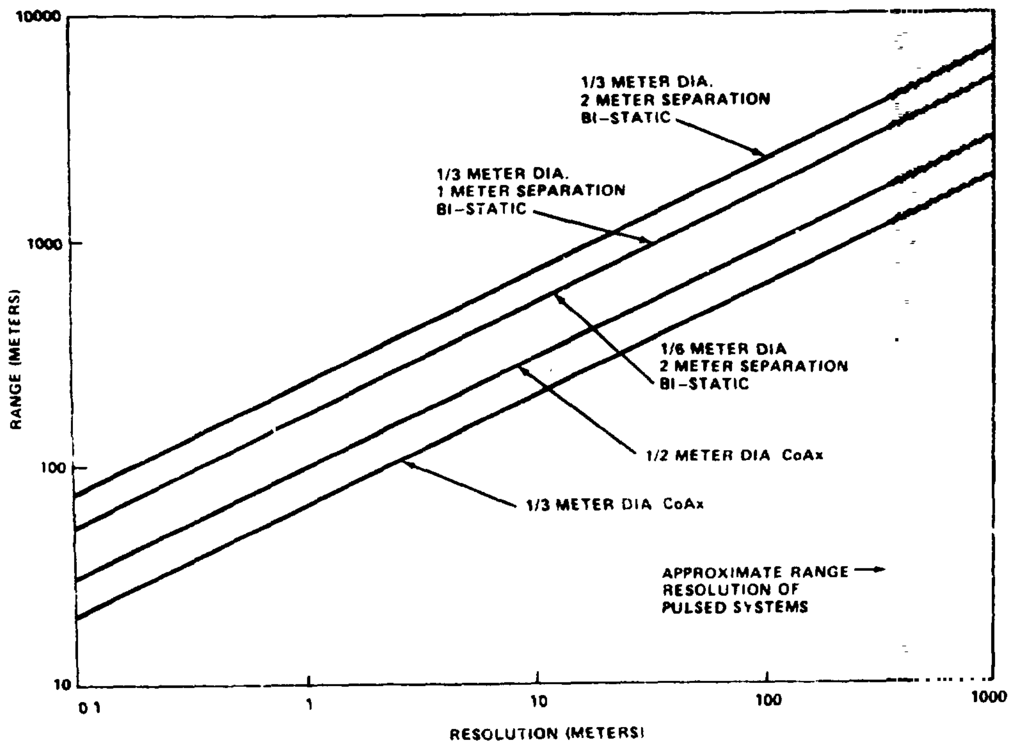


FIGURE 12. RANGE RESOLUTION OF $CO_2$ LDV SYSTEMS

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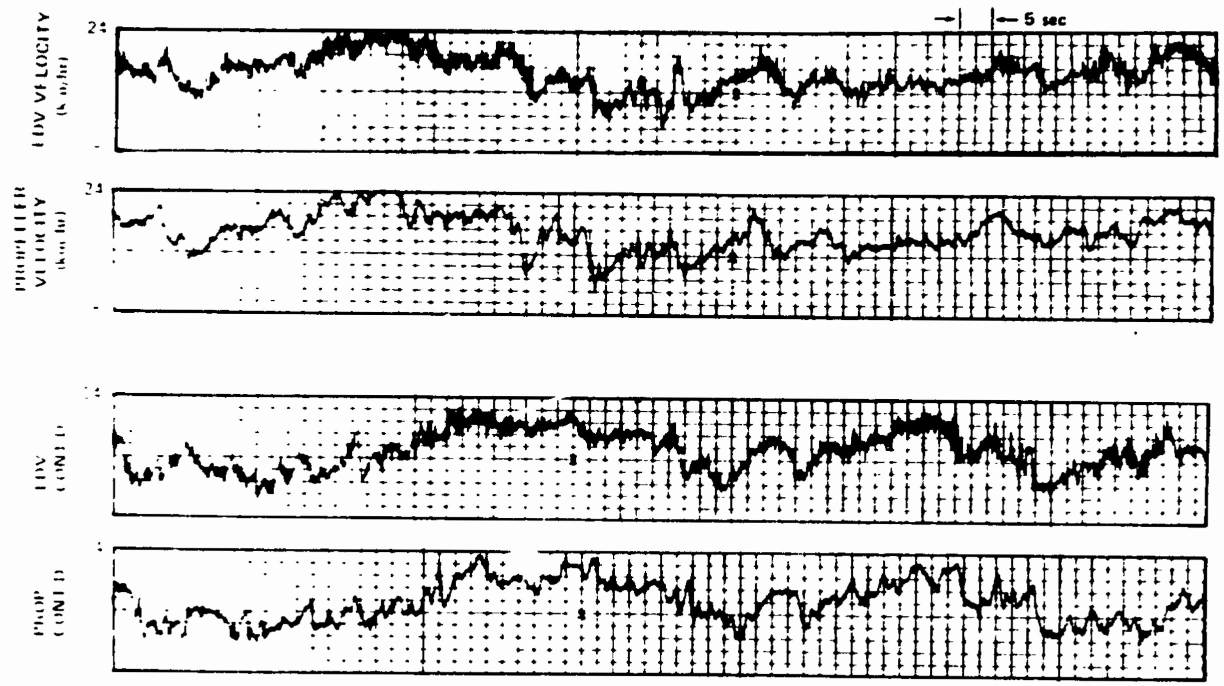


FIGURE 13. COMPARISON OF LDV RADIAL VELOCITY WITH A PROPELLER ANEMOMETER AT A RANGE OF 60 METERS

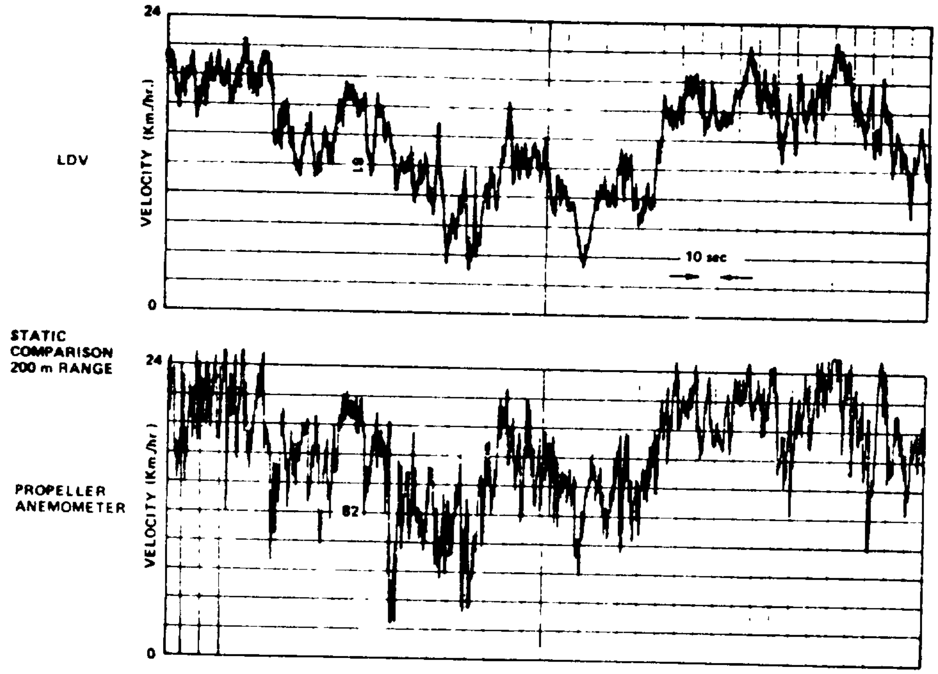


FIGURE 14. COMPARISON OF LDV RADIAL VELOCITY WITH A PROPELLER ANEMOMETER AT A RANGE OF 200 METERS.

that the volume sensed by the cup anemometer and the $CO_2$ co-axial LDV system are, in general, different. The component of wind velocity measured with the anemometers and LDV system were the same.

Since the co-axial system gives only the axial component of velocity, three such systems could be slaved together to produce outputs which could give the three-dimensional velocity field at a given focal volume in space. This would be very similar to what was done for the forward scatter three-receiver case which was discussed earlier.

Another configuration of the co-axial $CO_2$ LDV system which has been employed at Marshall Space Flight Center is a conical scanning scheme [9,10]. A single electromagnetic system with a conical scanning scheme has been used previously with radar [11]. Figure 15 gives a schematic of a conical scan and the output from a conical scan.

Figure 16 shows a comparison of the horizontal wind measured with a conical scanning $CO_2$ co-axial LDV and a cup anemometer. The conical scan configuration appears to have great potential for measuring atmospheric velocities near the ground. The useful range of such a system is probably up to 500 meters.

Ranging the focal volume in the co-axial system is accomplished by moving the secondary. The ranging of the focal volume from 20 meters to 300 meters can easily be performed in less than one second. Presently MSFC is using co-axial $CO_2$ LDV systems and scanning in range and elevation while measuring atmospheric phenomena (such as airplane vortex location and wind fields).

3. Pulsed Co-axial LDV Systems

The pulsed co-axial LDV systems are similar to the co-axial systems mentioned above except that range location is performed by gating the Doppler return. Figure 12 shows the approximate location where range resolution for the pulsed system becomes better than the co-axial or bistatic CW configurations. MSFC has been developing a pulsed co-axial $CO_2$ LDV system to detect clear air turbulence. For the clear air detection system the pulse length is between 4 and 10 $\mu$ sec, and is pulsed at a rate of 140 to 160 times per second.

4. Dual Beam (CW) LDV Systems

The dual beam system employs the use of two beams crossing in space setting up a fringe pattern. When a particle

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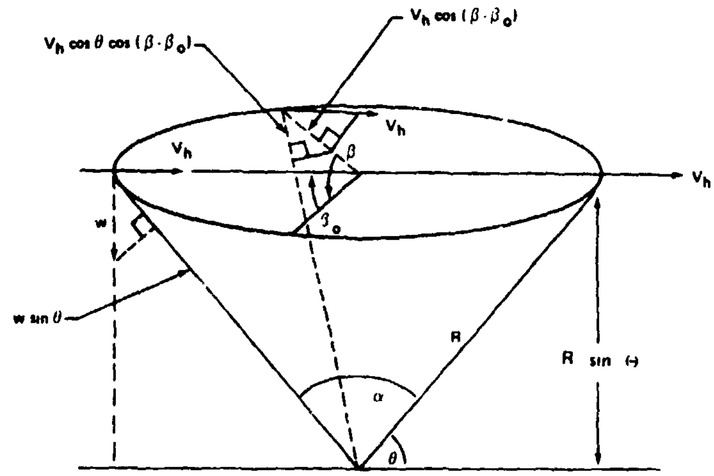


FIG. 15a VAD SCAN CONFIGURATION

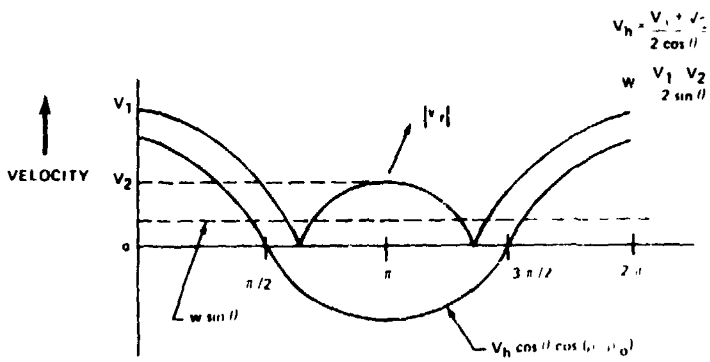


FIG 15b AZIMUTH ANGLE DEPENDENCE OF MEASURED VELOCITY COMPONENT

FIGURE 15. SCHEMATIC OF A CONICAL SCAN AND OUTPUT FROM A CONICAL SCAN

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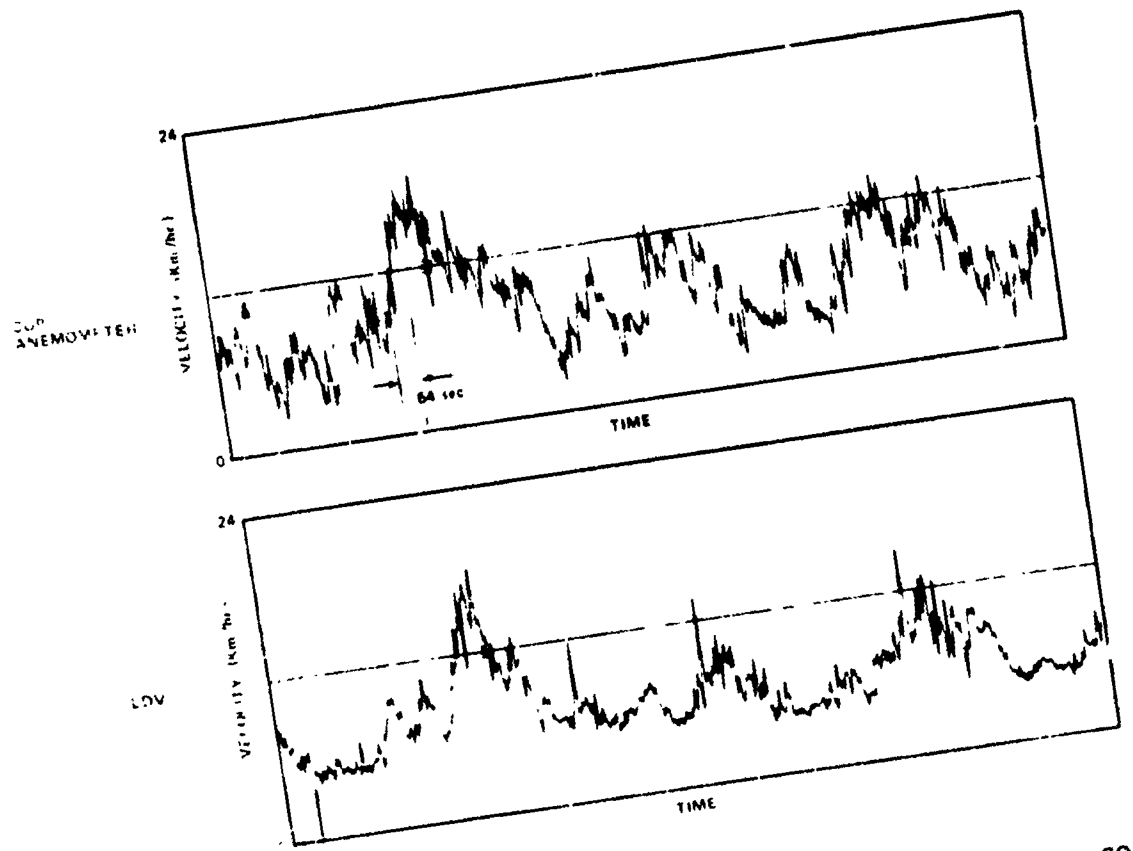



FIGURE 16. COMPARISON OF HORIZONTAL WIND MEASURED WITH A $CO_2$ CO-AXIAL LDV CONICAL SCAN SYSTEM AND A CUP ANEMOMETER AT AN ELEVATION OF 21 METERS (CONE ANGLE = 90°)

passes through the fringe pattern light is scattered in all directions, the frequency of which is determined by Eq. 1. A general dual-beam configuration was shown in Figure 3. The dual-beam systems have the advantage that when the beams are crossed, the Doppler frequency may be measured from any location in space. That is, the Doppler shift is a function of the angle of intersection of the beams. However, it should be noted that scattering intensity and thus intensity received at a photodetector may be very much dependent on spacial location of the detector. In general the forward scatter is much stronger than the backscatter, as is indicated from Mie scattering theory. Another advantage of the dual-beam system is that it measures directly the transverse velocity component, whereas the co-axial system measures the axial component. These systems are generally employed in the laboratory where the range from the laser to the crossing point (fringe area) is small (generally less than two meters). One of the drawbacks of the system is the fact that as you increase range it becomes increasingly difficult to align the system so that there is an actual crossing of the two beams. Also, since the optical path of the two systems is different, the local index of refraction along each beam path could change and cause the beams to wander slightly in time. Similar problems would occur should one attempt to focus a receiver and a laser at the same point in space. Because of these difficulties it is easier to employ a co-axial system for atmospheric use at the present time.

## 5. Single Particle Dual-Beam LDV Systems

Single-particle, dual-beam Doppler systems are presently being developed at Ames Research Center. The concept is to examine the statistics of each particle that passes through the fringe pattern. Selective sampling electronics are used to eliminate signals produced by particles that do not pass directly through the fringe pattern or signals produced by multiple particles passing through the fringe pattern simultaneously. Since no continuous signal is achieved by this method, each particle velocity statistic is used to develop a probability density distribution. From the probability density distribution the statistics of the flow field are then calculated. That is, $\overline{U^n} = \int_{-\infty}^{\infty} U^n P(U)\, dU$, where U is the velocity of the particle, P(U) the probability distribution of the velocities, and the $(\overline{\ \ })$ indicates the mean of the bracketed quantity. In the continuous output cases, time averages would be used. The advantage of a single-particle LDV system for wind tunnel work is that no seeding of particles should be necessary. That is, the naturally occurring aerosols should be sufficient to operate the system. In wind tunnel flows, seeding of the flow may be necessary to obtain a continuous signal from the sensing volume for continuous types of LDV systems. In water or in the atmosphere there are generally sufficient particles to produce a continuous signal from a typical LDV focal volume.

## B. TYPICAL WAVELENGTHS AND COMMON USES OF LASERS PRESENTLY IN USE IN LDV SYSTEMS

1. Helium Neon:

    a. Wavelength: 0.6328μ (visible)

    b. Uses: Dual-beam systems for short range systems.

2. Argon:

    a. Wavelengths: 0.5145μ and 0.4880μ (visible) (NOTE: There are about 8 useable lines in an argon laser. The two listed above are the strongest.)

    b. Uses: Dual-beam systems for short range systems.

    Dual-beam, single-particle short range systems.

    Local oscillator bistatic systems for short range.

3. $CO_2$:

    a. Wavelength: 10.6μ (infrared)

    b. Uses: Local oscillator bistatic and co-axial long range (atmospheric to 500 m).

    Dual-beam medium range (10 m)

    Pulsed co-axial long range (atmospheric to 10 km).

## C. CONCLUSIONS AND RECOMMENDATIONS CONCERNING LASER DOPPLER SYSTEMS

1. The laser Doppler system measures the velocity of particle tracers imbedded within the flow. The particle velocity is then related to the fluid velocity. It is anticipated in many cases that the particles move with the same velocity as the fluid surrounding the particle, such as was shown in Figure 10.

2. The basic laser Doppler systems presently in use are:

   a. Local oscillator - continuous wave

   b. Local oscillator - pulsed

   c. Dual-beam - continuous wave - continuous signal

   d. Dual-beam - continuous wave - single particle realization

3. Typical scanning methods are:

   a. Focusing the Doppler system at a point and then moving the entire laser Doppler system to move the focal point.

   b. With the co-axial type system, range scanning is performed by manually or electronically moving the secondary mirror. A finger type scan can be performed with this configuration. By continuously varying the pointing angle along with the range, a plane may be scanned.

   c. Using the co-axial system focused at a given range, the following scan patterns have been used.

      (1) Conical scan: A rotating mirror moves the focal volume in a circular path in space. The three-dimensional velocity field at a given elevation is measured with this method. By ranging the focal volume as the beam is rotating, it is also possible to get a spiral conical scan which could give an altitude velocity profile.

      (2) Two-point scan: A mirror flips back and forth, sending the focal volume back and forth between pre-selected points. The sum and difference of the velocities measured may be used to compute a longitudinal and lateral component of velocity. (This scheme has not proven very successful in the past.)

      (3) Ranging focal location with moving mirror: A mirror is set on an air track such that the mirror is moving at a constant velocity while the laser beam strikes the mirror (before the focal volume). The moving mirror scheme thus

moves the focal volume and gives the same effect as though the system was moving relative to the particles. MSFC used this scheme to investigate artificial fogs at an Ames Research Center fog chamber.

4. For wind tunnel flows where a transverse one-dimensional velocity is needed, the dual-beam systems are used frequently.

5. A three-receiver forward scatter LO LDV system has been used to measure (on line) the turbulent three-dimensional velocity field of a fully developed gaseous pipe flow.

6. Direct comparison of velocities measured with a hot wire and laser Doppler system have been performed and shown to be in good agreement. (This does not mean, however, that this is always the case. The experimenter has to be careful to be confident that the particle (tracer) velocity is the same as the velocity of the fluid around the particle.)

7. A laser Doppler system without a frequency translator has a direction ambiguity of $180^{o}$. The Doppler frequency is the absolute difference between the frequency of the laser and scattered radiation. The use of a frequency translator allows the sense of the direction to be determined.

8. In many wind tunnel type gas flows, seeding of particles may be necessary to retrieve a continuous signal from the LDV focal volume.

9. The use of low pass filters is recommended to eliminate high frequency noise.

10. Laser Doppler systems have shown excellent promise as a velocity measuring tool. The laser systems are superior to acoustic systems for defining small resolution volumes.

## IV. ACOUSTIC DOPPLER

The acoustic Doppler, like the laser Doppler, works on the basic principal that radiation incident on a moving tracer is shifted in frequency in accordance with Eqs. 1 through 4. The tracers in the naturally occurring atmosphere which scatter the acoustic radiation are velocity and temperature gradients. That is, the acoustic Doppler systems measure the velocity at which velocity and temperature gradients are translated or convected through the atmosphere. The equation for the scatter of sound in dry air is given by Beran (1974) [12] as:

$$dG = \frac{2\pi K^4 V \cos^2\beta \; d\Omega}{\left[\frac{E(K)}{C^2}\cos^2\frac{\beta}{2} + \frac{\phi(K)}{4T^2}\right]^{-1}} \qquad (9)$$

where dG is the fraction of the incident acoustic power which is scattered by irregularities in volume, V, (the scattering volume) through an angle $\beta$ into a cone of solid angle $d\Omega$. The spectral intensities of the velocity and temperature fluctuations are given by E(K) and $\phi(K)$, respectively, and the speed of sound and mean temperature are given by C and T, respectively. Eq. 9 shows that the scattered acoustic radiation attributed to the velocity inhomogeneities is dependent on both the scattering angle, $\beta$, (180 - $\theta$), and the scattering angle divided by 2, $\beta/2$. The latter case shows that the velocity inhomogeneities produce no scatter in a complete backscatter mode, $\theta = 0$. Using the fact that pure backscatter contains no information from velocity inhomogeneities, Lran points out that an acoustic Doppler in pure backscatter mode has the disadvantage that some areas of the atmosphere may not have sufficient temperature gradients to produce a good Doppler return.

## A. TYPES

The acoustic Doppler may be broken into two simple classes. They are pulsed and continuous wave.

### 1. Continuous Acoustic Doppler

The continuous acoustic systems, as the name implies, are operated using a continuous source. To use a continuous source, one would like to isolate a particular sensing volume by focusing, just as was done with the laser Doppler systems. The focusing could conceivably be performed by employing focusing for both the transmitter and receiver or possibly just focusing the receiver on some portion of the transmitted beam. A co-axial (pure backscatter) continuous acoustic Doppler system appears difficult at present because the returning and emitted acoustic radiation may not easily be separated as was the case with the laser Doppler.

Presently the most feasible configuration for a continuous wave (CW) acoustic Doppler system is the bistatic configuration where the source and receiver are at spacially separated locations. As with the laser Doppler, more than one receiver could be employed to obtain two- and three-dimensional information. A schematic of a three-dimensional CW acoustic Doppler is shown in Figure 17.

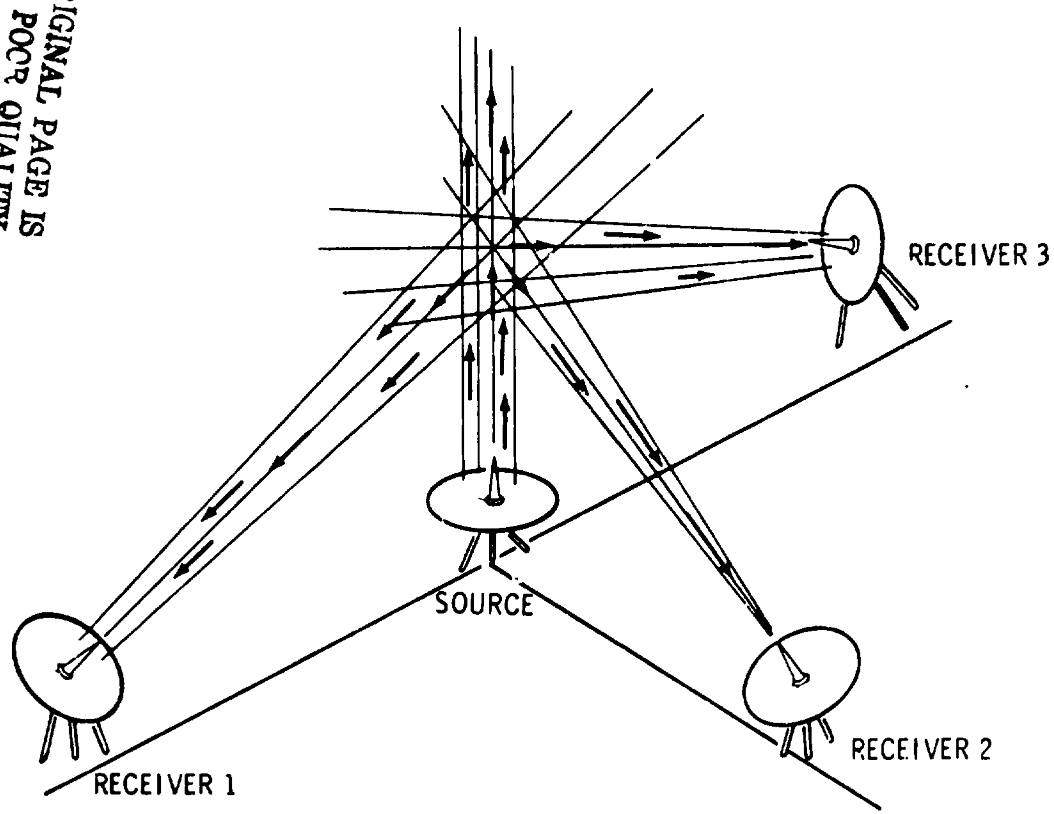



FIGURE 17. SCHEMATIC OF A 3-D CW ACOUSTIC DOPPLER

The acoustic Doppler systems work in frequency ranges easily handled electronically (generally 400-4000 Hz); thus, it is not necessary to use the heterodyning process as was necessary with the laser Doppler systems. Instead, it is desirable to measure the return frequency directly, which allows direct determination of the sense of the flow. In the laser Doppler case it was pointed out that beating the scattered radiation with the source radiation created a beat frequency with an ambiguity of 180° in flow direction (it is noted that a frequency translator employed in the source radiation corrects the ambiguity probl .). To date it has been difficult to sufficiently isolate the receiver of the CW acoustic Doppler system to eliminate source noise from swamping out the scattered radiation.

2. Pulsed Acoustic Doppler

The pulsed acoustic Doppler system is able to avoid the contamination of source noise by simply not sampling until after the source noise has passed the receiver. That is, since the path length taken by the scattered acoustic radiation is longer than the path length from the source to the receiver, the transit time for the scattered radiation to reach the receiver is longer than for the source noise. The elimination of source noise is shown in Figure 18.

As with the CW acoustic Doppler, the pulsed acoustic Doppler benefits from using a bistatic configuration instead of a co-axial system. This is due to the fact that in the co-axial mode only radiation scattered by temperature gradients is measured, while in the bistatic mode scattering from both velocity and temperature gradients contributes to the received radiation [13-15]. A pulsed system with a configuration similar to that shown in Figure 17 could be used for three-dimensional velocity measurements. If one considers the average vertical velocity to be small, the horizontal two-dimensional velocity could be measured by using only two non-coplaner receivers shown in Figure 17. A system as was just described has been used in atmospheric research by Beran and Clifford of NOAA[16]. Figure 19 is a comparison of the horizontal atmospheric wind sensed at an elevation of 150 meters using a two-receiver pulsed acoustic Doppler system and a tethered kytoon (small blimp called Boundary Layer Profiler, BLP) which had sensors for measuring horizontal wind. (Figure 19 was taken from reference 16, courtesy of Dr. D. W. Beran of NOAA, Boulder, Colorado.) The acoustic radiation was pulsed from a vertically pointing source. Two receivers forming a right angle with the source were employed. The elevation of the sensing volume was determined by selectively gating the return such that only scattering

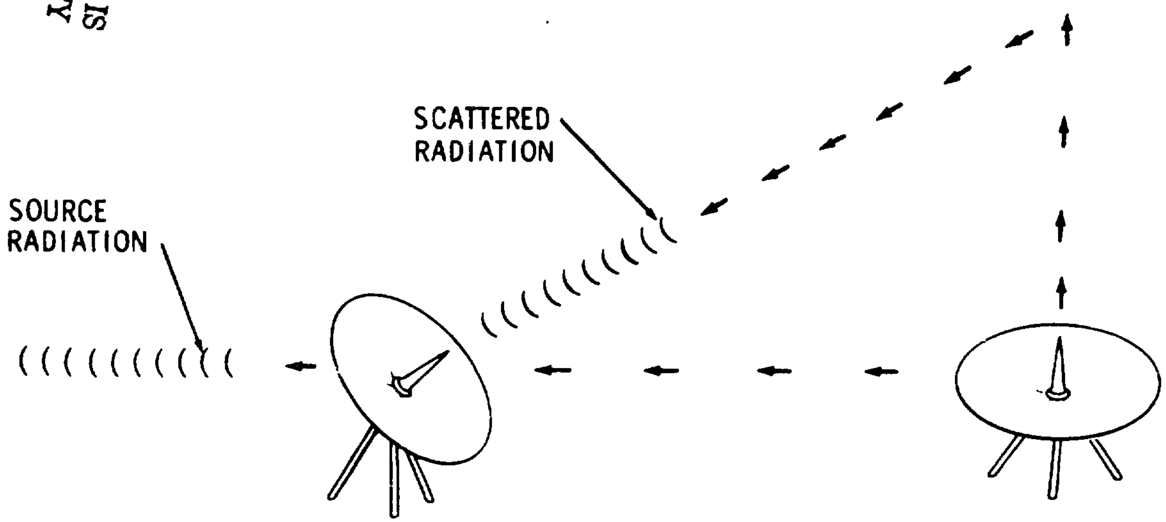



FIGURE 18. SCHEMATIC OF SOURCE NOISE ELIMINATION BY PULSED ACOUSTIC DOPPLER SYSTEM

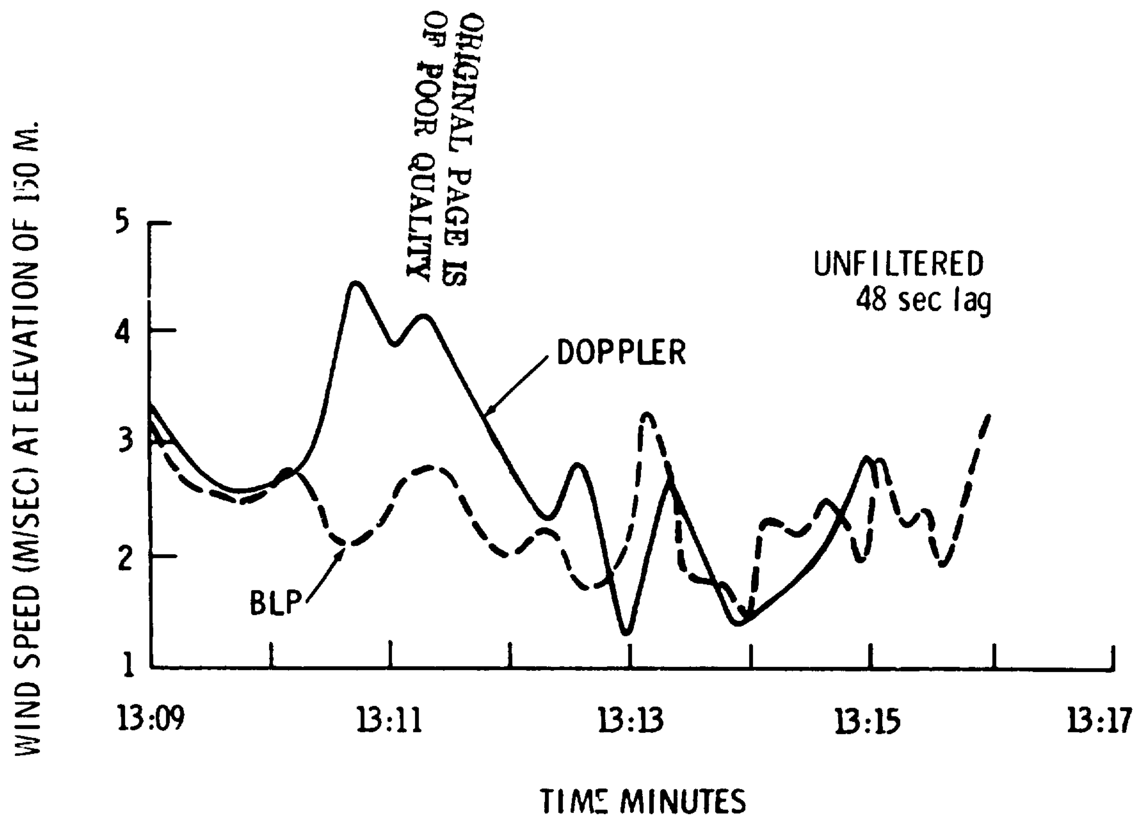



FIGURE 10. WIND VELOCITY COMPARISON OF PULSED ACOUSTIC DOPPLER AND BOUNDARY LAYER PROFILER (COURTESY OF DR. D. W. BERAN, NOAA, BOULDER, COLORADO).

from a particular elevation would be arriving at the receiver during the sensing time. Gating the return in this way permits the receiver to be non-focused, nearly accepting acoustic radiation from a general direction.

The NOAA systems as described by Beran [17] are presently employing 3 m parabolic dishes for receivers and sources. The parabolic configuration is used to develop a near parallel acoustical emission. The emission is 50-60 watts. Present plans are to go to a 4 m by 4 m array of 144 speakers with 500-600 watts. The present resolution volume is approximately 30 m by 30 m using an 0.5-second pulse every 8 seconds. The pulse duration may be shortened if there is sufficient power. The source frequency is generally 400-4000 Hz.

The use of acoustic Doppler systems is also being investigated for use in measuring blood flow [18-20]. The scattering source of interest in this case is the red blood cell, $\sim 10\mu$ in diameter. The ultrasonic Doppler is used for nondestructive remote investigation of blood flow. The sound waves are able to nondestructively penetrate the skin, tissue, and blood vessels, which also scatter sound at the interfaces but, since no motion is occurring do not shift the frequency of the scattered acoustic radiation. Along with the red blood cells, the white blood cells and platelets will also be scattering sources but due to the smaller size and smaller percentage of mass, the white blood cells and platelets do not contribute significantly to the received Doppler return [20]. In order to analyze the depth, a co-axial pulsed system is generally used. Figure 20 is a schematic of such a system. Comparison of the expected flow pattern vs the ultrasonic Doppler measured flow pattern for poiselle flow in a 7.2 mm diameter tube is presented in Figure 21a (courtesy of Dr. M. Wells, Colorado State University). Figure 21b presents a velocity profile in a horse's artery measured with an ultrasonic Doppler system (courtesy of Dr. M. Wells, Colorado State University).

In order to get adequate spacial resolution to interrogate flow in veins and arteries, ultrasonic frequencies are employed. Frequencies used range from 8-20 MHz, and may go as high as 40 MHz. Some problem areas associated with the use of a co-axial pulsed ultrasonic Doppler system for investigating blood flow are:

(1) The evaluation of the angle $\beta$ (see Figure 20).

(2) Getting a good measure of the cross sectional area of the vessel to use with the velocity to estimate mass flow rate. The resolution of the system may not be small compared to the channel diameter.

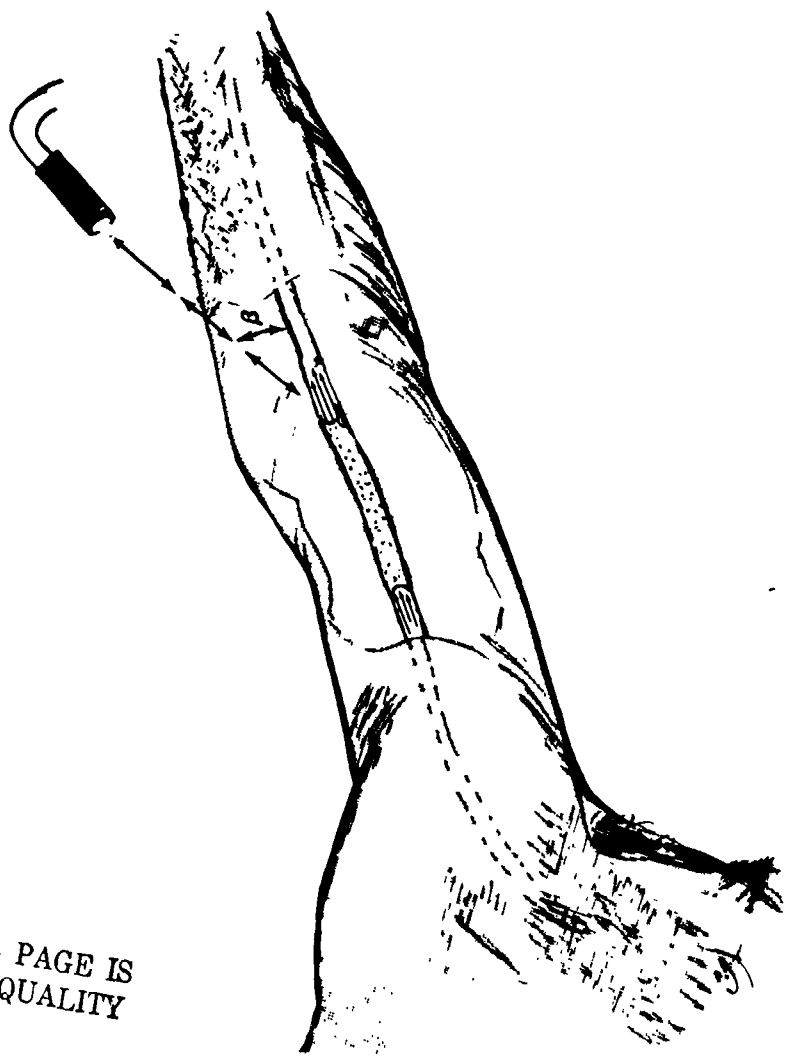
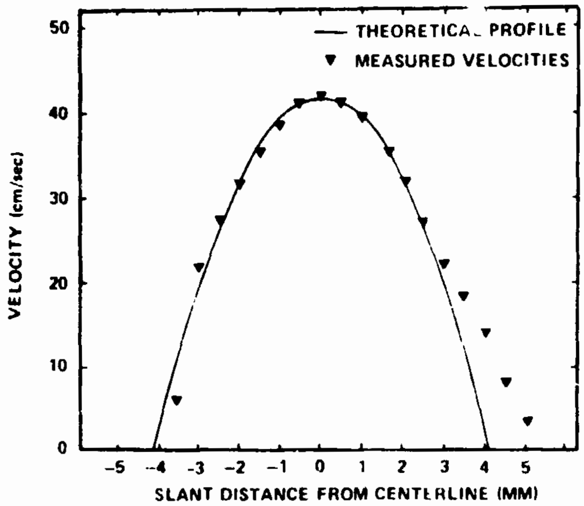
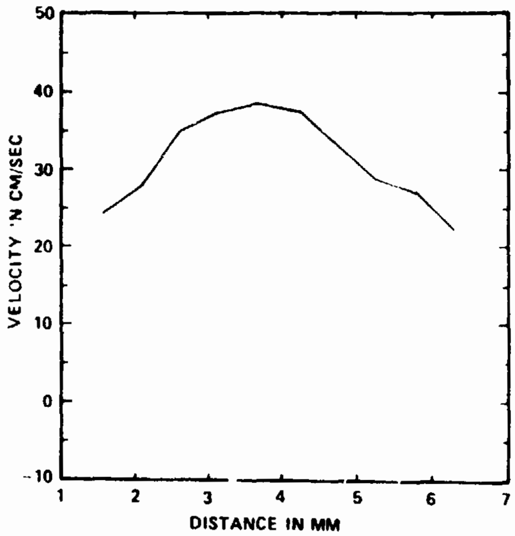


FIGURE 20. CUT-AWAY SHOWING ULTRASONIC DOPPLER SCHEME FOR INVESTIGATING BLOOD FLOW




A) VELOCITY PROFILE IN A 7.2 MM TUBE MEASURED WITH AN ULTRASONIC DOPPLER SYSTEM.




(b) VELOCITY PROFILE IN A HORSES ARTERY MEASURED WITH A PULSED ULTRASONIC DOPPLER SYSTEM

FIGURE 21. VELOCITY PROFILES MEASURED WITH A PULSED ULTRASONIC DOPPLER SYSTEM (COURTESY OF DR. M. WELLS, COLORADO STATE UNIVERSITY)

## B. CONCLUSIONS AND RECOMMENDATIONS CONCERNING ACOUSTIC DOPPLER SYSTEMS

1. Presently the performance of the pulsed acoustic Doppler systems appears superior to the continuous wave acoustic Doppler.

2. Acoustic Doppler techniques appear to be viable candidates for the remote sensing of the motion of the temperature and velocity gradients in fluid motions.

3. The ability of the temperature and velocity inhomogeneities to follow the mean motion is the criterion employed to interpret the results of an acoustic Doppler system for use as a mean wind detector.

4. Pulsed ultrasonic Doppler techniques are presently being used to investigate blood flow in animals. This appears to be an excellent area for future research in both pulsed and CW acoustic Doppler because of the nondestructive penetrability of animal tissue by acoustics. The scattering source producing a Doppler shift in this case is the cellular flow within the arteries and veins.

5. As with the laser Doppler systems, the acoustic Doppler measures the velocity of a scattering source. The velocity of the scattering source is then studied by itself or is interpreted as a tracer of the surrounding medium, and the motion and statistics of the tracer's velocity are used to infer the velocity and statistics of the medium in which the tracer is embedded.

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APPROVAL

LASER AND ACOUSTIC DOPPLER TECHNIQUES
FOR THE MEASUREMENT OF FLUID VELOCITIES

by

William C. Cliff

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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

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Director, Space Sciences Laboratory



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