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THE DELTA DOPPLER TECHNIQUE FOR LDV MEASUREMENTS AT LONG DISTANCES

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16. ABSTRACT

A technique for measuring velocity, referred to as a Delta Doppler technique, is presented. The Delta Doppler technique determines scattering source velocities by measuring the difference in Doppler shifts of two different frequencies. By transmitting the two frequencies along the same path, a moving fringe pattern is established such that a nonmoving scatterer at the sensing volume would see an intensity variation exactly equal to the difference in the transmitted frequencies. If the particle has a velocity component along an axis which bisects the angle formed by the transmitter and receiver axes, a Doppler shift in the difference frequency can be measured and the velocity component computed. The frequency measured would correspond to the difference in Doppler frequencies that two laser Doppler velocimeters using separate frequencies (the same frequencies as used previously) would have measured, thus the term Delta Doppler. The advantages of the Delta Doppler technique are: (1) Laser coherence length problems should be minimized; that is, the experimenter should not need to equalize separate path lengths as is required for crossing-beam fringe systems. (2) Visible lasers should be applicable for long-range Doppler atmospheric work; presently only CO_2 laser Doppler systems have proven successful for atmospheric research because of their long coherence length. (3) The frequencies measured could be much lower than present laser systems. The lower frequencies should reduce the cost of the electronic data reduction system employed.

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I. INTRODUCTION

Considerable emphasis in recent years has been placed on developing techniques to remotely measure the velocity of free and confined flows [1]. The laser Doppler system has emerged as a highly successful technique for measuring particle velocities embedded within flows. In general, the particle velocity is considered to be a tracer of the gas velocity surrounding the particle, and in many cases this has been found to be justified [2, 3].

Coherence length difficulties in wind tunnel type flows are presently avoided by simply matching the path lengths of the local oscillator beam and scattered beam for the local oscillator approach or by matching the two path lengths of crossing beams for the dual-beam, fringe approach. Coherence is a term used to describe the ability of the laser beam to efficiently optically mix with itself (homodyne). Two types of destructive effects are possible which decrease the coherence length of a system. One is a temporal coherence problem which is simply that the laser cavity may change the frequency it is amplifying. This problem may result from mode hopping, thermal expansion of the cavity, or a host of other factors which can cause the cavity's resonant frequency to shift in time. The second effect is a temporal coherence problem generally caused by more than one frequency being simultaneously emitted from the cavity. Just as in a Fourier series where sine waves act constructively or destructively to produce a repeatable function, so does a combination of frequencies being emitted from a laser cavity. Operation at long distances makes it inconvenient or impossible to match coherent lengths.

Operation of a laser Doppler system over long ranges creates another problem if a dual-beam approach is used. The problem is to keep the two beams physically crossing at a point in space. Because of this problem a pure backscatter coaxial laser Doppler system has proven to be highly advantageous. Here the laser beam is transmitted and received with the same optics. However, with this method it becomes increasingly difficult to match path lengths of the transmitted beam with a reference beam with which it can mix. The alternate approach is to use a laser with an extremely long coherence length. The CO_2 laser has been highly successful for this purpose; however, the CO_2 laser operates in the infrared (generally 10.6 μm) and requires a cooled detector. Therefore, a system which could use a visible laser, and thus noncooled photomultipliers for detection purposes, would be an improvement for certain applications. In general, visible lasers are also less expensive than CO_2 lasers with good coherence characteristics. The purpose of this report is to present a technique that is believed to provide a method for overcoming the coherence problem and, thus, allow visible lasers to be used for coaxial backscatter atmospheric velocity measurements. The technique could also be used in the laboratory where it is advantageous. The technique is called the Delta Doppler technique and measures a Doppler frequency equivalent to the difference of two Doppler frequencies measured by two systems using different local oscillator wavelengths.

II. BACKGROUND

The Delta Doppler technique is a method of measuring velocity by using two different radiation frequencies transmitted along the same axis and received along the same axis (the transmission axis may be different from the receiving axis, but this report will limit its scope primarily to the case in which the transmission and receiving axes are the same, coaxial) and measuring the difference in frequency received at the detector. The concept of laser Doppler velocimetry (LDV) has been well established in the open literature; see, for example, References 1-4. LDV is based on the fact that there is a change in frequency with which energy reaches a receiver when the receiver and energy source are in motion relative to one another; this is the well-known Doppler principle. The use of the difference of two independent Doppler shifts is utilized in the Delta Doppler technique as described in the next section.

III. THEORY

The Doppler frequency shift measured by a photodetector may be expressed mathematically as

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

where

n is the index of refraction,

$\bar{V}$ is the velocity vector of the tracer,

λ is the wavelength of the source radiation,

$\bar{e}_s$ is a unit vector along the scattered radiation (a unit vector from the scattering source to the receiver),

$\bar{e}_i$ is a unit vector along the incident radiation (a unit vector from the source to the tracer).

In all cases, the index of refraction of the medium is assumed equal to 1.0, and the term n (index of refraction) will not be shown in the following equations. If the index of refraction is different from the value 1.0, it must be used in equation (1) and carried throughout the remaining portion of the report.

From equation (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 between the incident and scattered radiation. Figure 1 presents a three-dimensional view of a single laser Doppler system. In Figure 1, the axes are oriented such that the velocity component sensed by the system lies along the z axis. Thus, any motion in the x-y plane would not be detected by the Doppler system. The use of additional Doppler systems would allow two- or three-dimensional velocity measurements, however.

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, equation (1) may be written:

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

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 the scattered radiation.

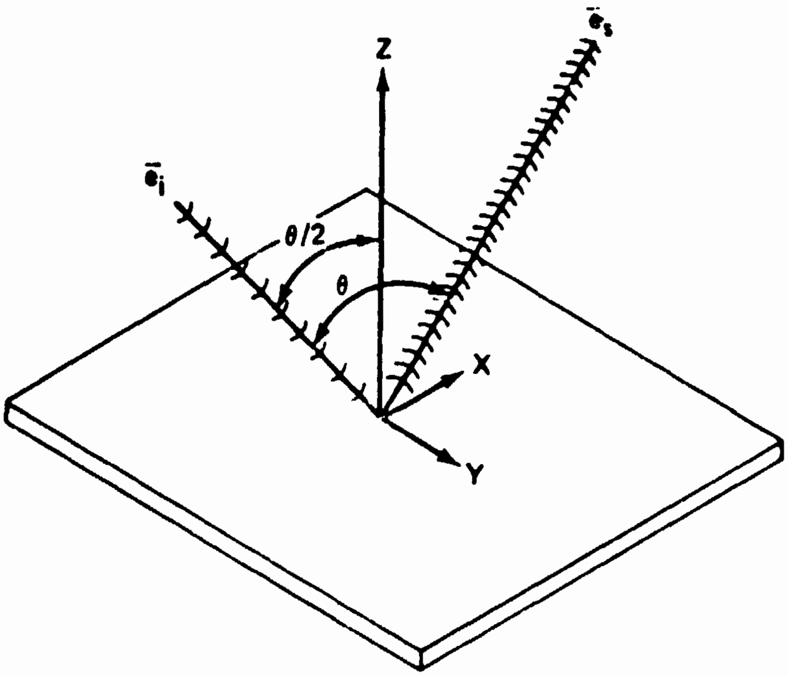


Figure 1. A three-dimensional view of a single laser Doppler system. (The plane formed by the lines of the incident radiation and scattered radiation is normal to the x-y plane.)

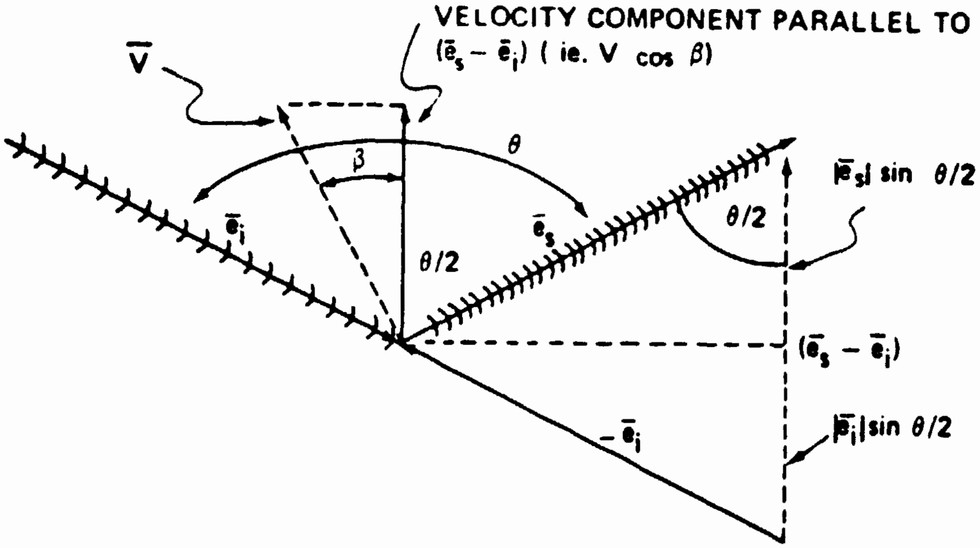


Figure 2. Plane view of a single laser Doppler system. (Only the component of velocity parallel to $(\bar{e}_s - \bar{e}_i)$ is detected.)

In terms of the velocity measured, V_m, equation (2) may be written:

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

If one measures pure backscatter (i.e., the detected scattered radiation traverses the same optical path as the emitted radiation, $\theta = 180°$), equation (3) becomes

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

IV. THE DELTA DOPPLER PRINCIPLE

The Delta Doppler technique measures the difference in the Doppler frequencies detected by two laser systems operating simultaneously along the same paths and using different optical frequencies (wavelengths). From equation (3) the Doppler frequencies measured by the two systems would be:

$$\Delta f_1 = \frac{V_m 2 \sin \frac{\theta}{2}}{\lambda_1} \tag{5}$$

and

$$\Delta f_2 = \frac{V_m 2 \sin \frac{\theta}{2}}{\lambda_2} \quad . \tag{6}$$

Since the systems are operating in exactly the same geometrical configuration, the difference in the Doppler frequencies would be

$$Df = \Delta f_1 - \Delta f_2 = 2 V_m \sin \frac{\theta}{2} \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \tag{7}$$

where Df is the difference of the Doppler frequencies, or the Delta Doppler frequency, which may be rewritten as

$$Df = 2 V_m \sin \frac{\theta}{2} \left(\frac{f_1 - f_2}{c} \right) \tag{8}$$

where c is the velocity of light and $c/\lambda_1 = f_1$ and $c/\lambda_2 = f_2$. Now defining $\delta f = f_1 - f_2$, equation (8) becomes

$$Df = 2 V_m \sin \frac{\theta}{2} \frac{\delta f}{c} \quad . \tag{9}$$

Equation (9) is the basic equation for the Delta Doppler principle. It should be noted at this point that from equation (9) the Delta Doppler frequency is dependent on δf, which is the difference between the two transmission frequencies; if this difference can be made independent of the laser itself, the Delta Doppler frequency would be independent of the laser coherence. One such process may be accomplished by splitting the original laser beam, sending one portion through a frequency translating device, matching the path lengths, and recombining the beams for transmission. (The frequency translating device could be a Bragg cell, spinning disk, rotating half-wave plate followed with a quarter-wave plate, etc., although the Bragg cell certainly seems to be the most versatile method at the present time.) If a frequency translating device is employed, the difference in frequency between the beams, δf, is only a function of the frequency translating device, the velocity being measured, and the geometrical angle of scatter. Thus, the coherence of the Delta Doppler process for this example is only a function of the stability of the translator. This should allow poor coherence lasers to be used for long-range laser Doppler type research by utilizing the Delta Doppler principle.

A nonlimiting example of the Delta Doppler principle utilizing a translator could be as follows. Consider an argon laser operating in a pure backscatter mode (equation 4 applies) on the 0.5145 μm line. Consider also that the beam is split and one part runs through an acousto-optical modulator (Bragg cell), shifting the frequency up by 300 MHz (an easily realizable shift with commercial systems).

From equation (9) the Delta Doppler frequency shift would be

$$\mathrm{Df} = 2\,V_m \left(\frac{3 \times 10^8 \text{ cycles/s}}{2.9986 \times 10^8 \text{ m/s}}\right) \simeq 2 \text{ Hz/m/s} \quad .$$

Thus, a frequency shift of 300 MHz gives a Delta Doppler frequency of only 2 Hz/m/s. This would not allow a fine resolution of velocity but would be useable for measuring very high velocities.

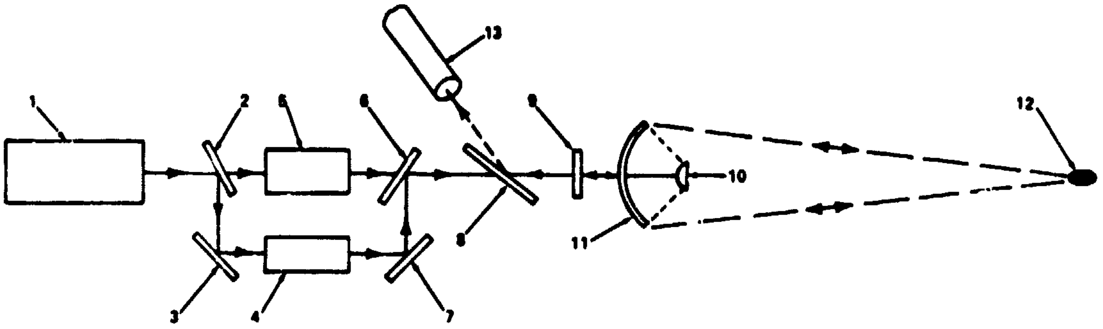
For a second case consider the argon laser simultaneously operating on the 0.5145 μm and 0.488 μm lines (at which the argon laser normally operates if it is not prismatically or otherwise selectively tuned). The Delta Doppler equation would be

$$\mathrm{Df} = 2\,V_m \left(\frac{1}{0.488 \times 10^{-6}\text{m}} - \frac{1}{0.5145 \times 10^{-6}\text{m}}\right) \sim 211 \text{ kHz/m/s} \quad .$$

In this case, the 211 kHz/m/s would allow extremely fine resolution.

Figure 3 gives a schematic of a system which could be employed for case 1. The laser beam would be split at point 2, and the path lengths from 2-5-6 and 3-4-7-6 would be matched. The lower beam would be translated up in frequency at position 4. The beams would be recombined at position 6 and would then pass through the Brewster window and become circularly polarized by passing through the quarter-wave plate. The beams would then strike the secondary mirror (where a small amount of radiation would be scattered directly back and would be used for heterodyning on the photomultiplier), go to the primary mirror, and be focused to a volume at point 12. Particles passing through the focal volume would scatter radiation back to the primary, to the secondary, and through the quarter-wave plate, becoming horizontally polarized and deflecting off the Brewster window into the photodetector, beating with a small amount of radiation which is reflected directly back from the secondary. If two modes are from the same laser (as in case 2), optics 2 through 7 are climinated.

The Delta Doppler detection is thus completed. A more optimum optical configuration for the beams after they pass point 6 can be found in Reference 4.



1 LASER
2 BEAM–SPLITTER
3 FIRST SURFACE MIRROR
4 BRAGG CELL
5 OPTICS FOR MATCHING PATH 2–5–6 AND 2–3–4–7–6
6 BEAM–SPLITTER
7. FIRST SURFACE MIRROR

8. BREWSTER WINDOW
9. QUARTER WAVE PLATE
10. SECONDARY MIRROR
11. PRIMARY MIRROR
12. FOCAL VOLUME
13. PHOTO DETECTOR

Figure 3. Schematic of a coaxial backscatter laser Delta Doppler system. (Note: This configuration measures the axial component of velocity.)

V. CONCLUSIONS

a. The Delta Doppler frequency is a function of the difference between the two frequencies being transmitted.

b. If the difference between the two transmitted frequencies is independent of the coherence of the laser, then the Delta Doppler frequency is independent of the coherence of the laser.

c. The Delta Doppler technique permits Doppler returns of low frequency.

d. The Delta Doppler technique should permit the use of poor coherence lasers for long-range laser Doppler research.

e. The system calibration is dependent only on the frequency difference between the two beams. In the case where one of the beams is translated, the system calibration is dependent only on the frequency translation and not on the laser frequency.

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APPROVAL

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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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