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TOOLS OF OCEANOGRAPHY

A Laser-Doppler Velocimeter with Ocean Applications[1]

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ABSTRACT

Difficulties of intrinsic and environmental origins are still being experienced in the use of ocean currentmeters. The recently developed laser-Doppler technique of flow measurement offers advantages over existing techniques and the application of the laser-Doppler technique to ocean flow measurements is proposed. In particular, a laser-Doppler system which has been used in the laboratory and which is suitable for ocean applications is described. This system is capable of an accuracy of a few percent even for very low speed flows (~ 0.1 cm/sec), a spatial resolution of about 0.5 cm and a temporal resolution of about 0.5 hz and these resolutions can be improved by simple design changes. A design for a cable-mounted, ocean current-meter based on this system is presented. The advantages and disadvantages of this currentmeter with respect to existing currentmeters are discussed.

1. *Introduction.* The laser-Doppler technique for fluid flow measurement was first demonstrated by Yeh and Cummins (1964). These authors showed that the Doppler shift of laser light scattered by tiny particles in moving water could be detected by mixing (heterodyning) the scattered light with some of the original laser radiation. The amount of literature on aspects of the laser-Doppler technique and its applications is substantial; bibliographies and reviews are available (Disa, 1972; Durst, Melling and Whitelaw, 1972; Van Dyke and Vincenti, 1973). Since problems of both fundamental and applied origins are

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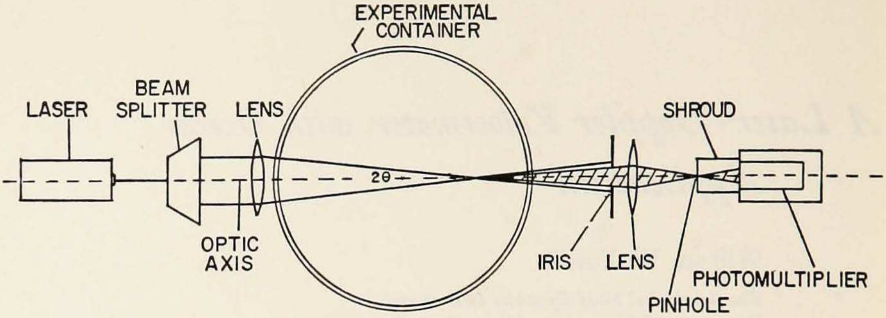

Figure 1. A schematic drawing showing the essential geometry of the dual-scatter laser-Doppler system.

being experienced with existing ocean currentmeters and since the laser-Doppler technique offers advantages over existing techniques, the authors are proposing the use of the laser-Doppler technique for ocean flow measurements. In this paper a laser-Doppler system which has been used in the laboratory and which is suitable for ocean applications is described (Fowlis and Martin). The additional requirements for using the system in the ocean are discussed and a currentmeter design is presented. The advantages and disadvantages of this currentmeter with respect to existing currentmeters are discussed.

2. *Description and Principles of the Laser-Doppler System.* Figure 1 is a drawing showing the essential geometry of the system. This arrangement was chosen because of the ease with which it can be aligned. The original laser beam is split into two parallel beams by the beam splitter. A lens then focuses these beams to a common point within the fluid. This cross-over point defines the position of the measurement and the volume of intersection of the beams is related to the spatial resolution. On emerging from the fluid region the beams are terminated on an iris. Light scattered by particles in the beams passes through the iris to a second collecting lens which focuses the scattered light onto a pinhole. By adjusting the distance between the lens and the pinhole and the pinhole diameter, only scattered light from the cross-over volume passes through the pinhole and reaches the photodetector. This arrangement is known as the dual-scatter or fringe system (Rudd, 1969).

A particle passing through the cross-over volume scatters light from both incident beams. Because of the angle between these beams (2η), the scattered light from each beam is Doppler shifted by a different amount. Heterodyning of these two frequencies by the photodector produces the difference frequency.

$$v_D = \frac{2n \sin \theta}{\lambda} V, \tag{1}$$

where n is the refractive index of the fluid, λ is the wavelength of the laser radiation (in vacuo) and V is the component of the flow perpendicular to the optic axis of the system and in the plane of the laser beams. Actual values for the laboratory system were: laser beam power $\simeq$ 5 milliwatts, $\lambda = 6.33 \times 10^{-5}$ cm (He-Ne laser), focal length of focusing lens $\simeq$ 17.5 cm, focal length of collecting lens $\simeq$ 7.5 cm and $2\theta = 5°20'$. These values give in water, $2n \sin \theta/\lambda = 1960$ cm^{-1} and hence for low flow speeds v_D was in the audio range. The overall length of the laboratory system was about 1 m.

If we assume the focusing lens (focal length f) to be diffraction limited, the cross-over or scattering volume is determined from the diffraction-limited spot sizes of the focused beams (Adrian and Goldstein, 1971; Edwards, et al., 1971; George and Lumley, 1973). The original laser beam has a Gaussian intensity profile described by $\exp(-8r^2/d^2)$ where r is the spatial variable in the plane perpendicular to the beam axis and d is the distance between the $1/e^2$ points of the intensity profile. The scattering volume is an ellipsoid whose center is on the optic axis and in the focal plane. Surfaces proportional to constant intensity are given by,

$$I = E_0^2 \exp\left\{-\left(\frac{x^2}{2\sigma_1^2} + \frac{y^2}{2\sigma_2^2} + \frac{z^2}{2\sigma_3^2}\right)\right\}, \tag{2}$$

where (x,y,z) is a cartesian system with y along the optic axis, x is the plane of the beams, and z perpendicular to the plane of the beams. E_0 is the maximum amplitude of both beams and $\sigma_1 = \sigma/\sqrt{2}\cos\theta$, $\sigma_2 = \sigma/\sqrt{2}\sin\theta$, $\sigma_3 = \sigma/\sqrt{2}$ where $\sigma = \sqrt{2}\lambda f/\pi d$. The dimensions of this volume and hence the spatial resolution of the system can be defined as the distances between the $1/e^2$ points of the ellipsoid, i.e., $4\sigma_1$, $4\sigma_2$ and $4\sigma_3$. Using the laboratory system values of $d = 0.065$ cm, $f = 17.5$ cm and $2\theta = 5°20'$ we obtain $4\sigma_1 = 0.022$ cm, $4\sigma_2 = 0.47$ cm and $4\sigma_3 = 0.022$ cm. The rather large dimension, $4\sigma_2$, can be reduced by increasing θ.

There were sufficient scatterers in tap water to yield a Doppler signal but the signal-to-noise ratio was improved by adding scatterers. Polystyrene spheres of 0.5 micron diameter in a concentration of about 1 part in 3.5×10^5 (0.0003% or 4.5×10^7 particles/cm^3) were used. This concentration gives an average number of about 5,500 particles in the $1/e^2$ diffraction-limited scattering volume.

An analysis of the above system shows that the output of the photodetector for a single particle passing through the scattering volume consists of an *ac* and a *dc* part (Adrian and Goldstein, 1971; Edwards et al., 1971; George and Lumley, 1973). For a speed V in the x-direction the *ac* part consists of a frequence v_D with a Gaussian amplitude modulation. For many particles within the scattering volume, the output consists of the random phase addition of the individual particle signals. This randomness arises because we have no control over the times at which individual particles enter and leave the scattering volume. This results in amplitude and frequency modulation of the output and hence in a frequency broadening which is known as transit-time broadening (see below).

The velocity component V is determined from a measurement of the frequency v_D. Several different methods have been employed. The laboratory system used a zero-crossing counter preceded by a bandpass filter to remove the *dc* part of the signal and unwanted high frequency signals. The temporal resolution depends upon the sample time of the counter and v_D. For a flow speed of 1 cm/sec, $v_D = 1960$ hz, and for a sample time of 1 sec a frequency of 0.5 hz could be resolved. This resolution can be improved by increasing θ to increase v_D and reducing the sample-time.

In order to detect the audio frequency output, all sources of frequency broadening must be relatively smaller. Broadening can be due to: (1) Brownian motion of the scatterers, (2) velocity gradients across the scattering volume, (3) flow fluctuations within the scattering volume, and (4) the finite record from each scatterer as it passes through the scattering volume. The laser line width is not significant because the heterodyning of the scattered light is carried out with light from the same original laser beam but optical path lengths must be kept similar. Mixing of the longitudinal laser modes (Lengyel, 1971) produces frequencies in the 10^8 hz range which were removed by the filter.

Brownian motion of the scatterers results in Doppler broadening of the scattered light. For the above system, the results of Dunning and Angus (1968) give for the Doppler broadening for 0.5 micron diameter spheres dispersed in water a value less than 1 hz. Velocity gradient and flow fluctuation broadening are discussed by a number of authors (Goldstein and Adrian, 1971; Edwards et al., 1971; George and Lumley, 1973; these sources are only important for tiny eddies whose scales are close to the spatial resolution and for fluctuations more rapid than the temporal resolution. Such scales do not exist for most ocean flows.

For most applications the largest source of broadening will be that due to the finite record in time from each scatterer; it is known as transit-time broadening or the Doppler ambiguity (Pike et al., 1968). The Fourier transform of the signal for a single particle yields a Gaussian curve centered on v_D with a standard deviation V/σ_1. This is the well-known wave uncertainty principle. The transform of the many-particle signal is also a Gaussian curve centered on v_D with the same standard deviation (Adrian and Goldstein, 1971; George and Lumley, 1973). For the above values and for $V = 1.0$ cm/sec, $V/\sigma_1 = 180$ hz and this corresponds to a standard deviation in velocity of 0.092 cm/sec. An analysis of the accuracy of the zero-crossing-counting technique for the many-particle signal is given by Adrian (1971). In general, for relatively long sample-times and for a large signal-to-noise ratio, this error is much less than the standard deviation.

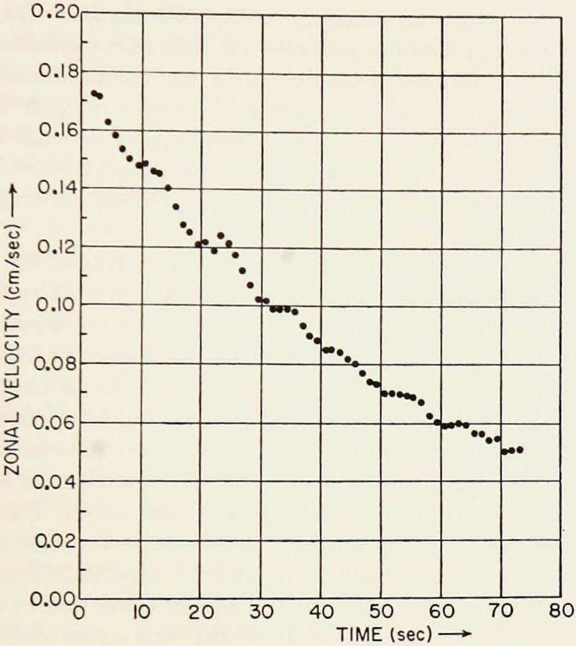

Figure 2. Measurements of the azimuthal velocity component generated in a cylinder of water by a change in the rotation rate of the turntable. Rotation rate change, from 18 to 20°/sec; position of scattering volume, radius 4.74 cm, height above cylinder base 3.00 cm; cylinder dimensions, diameter 18.970 cm, depth 5.987 cm.

The accuracy of this system, especially for low speed flows, is demonstrated by the following measurements (Fowlis and Martin). The system was mounted diametrically on a turntable and the beams crossed within a cylinder of water (see Figure 1). A small time-dependent relative azimuthal flow was generated by a small increase in the rotation rate of the turntable after the water had come to solid-body rotation. The results for an initial linear flow speed change of less than 0.2 cm/sec are shown in Figure 2. The relative flow decreases with time as the fluid spins up and the oscillations are real, being the natural inertial modes of the rotating fluid cylinder excited by the spin-up process (Greenspan and Howard, 1963). The sample-time for this experiment was 1 sec and for $V = 0.1$ cm/sec the standard deviation = 18 hz or 0.009 cm/sec. The "smoothness" of the curve in Figure 2 indicates a relative error of about ± 0.001 cm/sec or about ± 1% which is less than the standard deviation.

The system described above is sensitive to one flow component only. Rotation of the beam splitter in Figure 1 by 90° about the optic axis would make the system sensitive to the other flow component in the plane perpendicular to the optic axis. Alternatively, this could be achieved by having a duplicate system mounted with optic axis parallel to the original system but rotated by 90° with respect to it. It would not be necessary to duplicate the laser since the original beam could be split and used for both systems. The above systems involve temporal and spatial separations, respectively, for the measurements of the flow components; however, such separations could be made negligible for most ocean flow measurements. Multi-component laser Doppler systems in which the components are measured simultaneously at the same position in space have been devised (Fridman et al., 1968), but the experimental arrangements are complicated.

The system described above is sensitive to the magnitude of the velocity component but not to its direction. To obtain directional sensitivity, it is necessary to introduce a known, fixed frequency shift in one of the laser beams. If this frequency shift is v_R, the difference frequency will appear as $v_R \pm v_D$, instead of v_D, depending on the flow direction. Several methods for frequency shifting laser beams are available (Stevenson, 1970; Gordon, 1966) and directionally sensitive systems have been constructed (Denison and Stevenson, 1970). The method which consumes the least power and which is also the least expensive is to rotate a radial diffraction grating in one of the beams. The frequency of the diffracted light is shifted up or down by a constant multiple of the original frequency depending on which diffraction order is observed. The phenomenon responsible for this frequency shift is the Doppler effect due to the motion of the grating lines. The frequency shift of the first order diffracted light is given by,

$$v_R = \frac{\Omega N}{2\pi}, \tag{3}$$

where Ω is the rotation rate of the grating and N is the total number of lines on the grating. For typical values of $\Omega = 60$ rpm and $N = 5{,}000$, $v_R = 5{,}000$ hz.

3. *Requirements for Ocean Applications.* For immersion in the ocean the forward-scatter arrangement of Figure 1 will require two water-tight enclosures which are maintained in strict alignment. Figure 3 is a drawing of a proposed assembly which could be mounted on a cable and used to measure the horizontal flow vector. A cable-mounting assembly has been chosen for the purposes of discussion since it presents the greatest number of requirements and problems. The two horizontal flow components are determined by rotating the beam splitter and the flow direction by rotating the single circular radial diffraction grating which is arranged so that it intercepts one beam for each of the two splitter positions. For line mounting a simple internal compass and tilt-meter are required to determine the instrument orientation. Back-scatter systems also have been used in the laboratory and for atmospheric measurement (Farmer and Brayton, 1970). A back-scatter system would require only one enclosure but would require a more powerful laser.

He-Ne lasers with beam powers of a few milliwatts and a total power consumption of less than 10 watts which can be operated from low voltage batteries are commercially available. The laboratory system used a photomultiplier for a photodector but photodiodes can be used; they are small, inexpensive and consume very little power. The electronics required to amplify, filter and count the photodiode output can be relatively simple with low power consumption. The equipment required to average and store the count can be similar to standard current-meter systems.

Scatterers in the water are required for the Doppler technique. A sample of surface sea water taken from several hundred yards offshore in the Gulf of Mexico was added to the laboratory system container and an excellent signal was obtained. However, because data on the natural distribution of particles in the oceans is scarce, it cannot be said with certainty that over all the oceans sufficient scatterers exist to insure successful operation of the Doppler technique. Nevertheless, recent data from Beardsley et al. (1970) and Plank et al. (1972) indicate minimum particle densities of order $10^3/cm^3$ for particle sizes greater than 1 micron in diameter. Since most evidence indicates an exponential increase of particle number density with decreasing size, it appears that an adequate number density of scatterers does exist over most ocean areas.

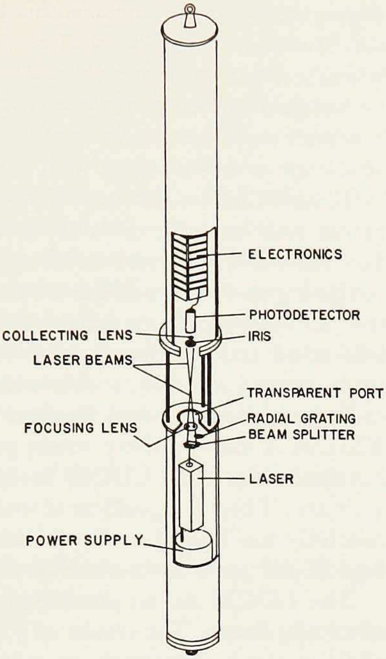

Figure 3. Drawing of proposed laser-Doppler ocean currentmeter. This meter is for cable mounting and horizontal flow measurement. The beam splitter is rotated through 90° for each component measurement and the radial diffraction grating is aligned so that for both component beam positions it intercepts one beam.

It will be necessary to prevent algae or other plants and animals from attaching themselves to the transparent ports of the enclosures through which the laser beams and scattered radiation must pass. The local presence of some copper and perhaps the strong laser light itself will reduce the presence of such growths. Fish are not sensitive to red light and hence will not be attracted by laser light in the red range.

4. *Advantages and Disadvantages of the Laser-Doppler System.* The laser Doppler system has advantages over conventional currentmeter systems. For the purposes of comparison let us consider the proposed currentmeter shown in

Figure 3. We shall compare this laser Doppler currentmeter (LDCM) with the Savonius rotor type of currentmeter (SRCM) (Richardson et al., 1963), with the electromagnetic currentmeter (EMCM) (Capart, 1969) and with the ultrasonic-Doppler currentmeter (UDCM) (Wiseman et al., 1972). In this paper we shall concentrate only on the essential differences which convey an advantage or disadvantage with respect to the LDCM.

The SRCM has serious problems associated with the response characteristics of the rotor and the direction vane. It has non-linear responses. There is a flow threshold of several cm's/sec below which the rotor does not rotate. Also oscillating movements of the meter can be rectified by the rotor. The EMCM is a recent development which awaits detailed studies. It has a very low threshold speed and a linear response over a wide speed range. However, its electrodes are mounted on a disk which is mounted in the flow and hence will cause some disturbance to the flow being measured. Another problem with the EMCM is the sensitivity versus power to excite the field coil. The UDCM has similarities to the LDCM but has not performed well for low speeds around 1 cm/sec. There is a problem of inadequate scatter of acoustic energy due to the relatively small number of particles of adequate size in clear open water. The beat frequency is lower than for the LDCM.

The LDCM has an exceedingly low speed threshold and its response is intrinsically linear. The results of Figure 2 show that flow speeds of 0.1 cm/sec and less can be accurately measured. Its spatial and temporal resolution are extremely good and it is capable of high sampling rates. In principle, it does not require calibration. Flow disturbances caused by the struts maintaining the two enclosures in alignment could be eliminated by mounting a vertical fin on the currentmeter in a position with respect to the struts such that when the fin aligned the meter with the flow, the struts would not be upstream or downstream of the scattering volume. The low flow speed capability of the laser-Doppler technique suggests its suitability in a design for a vertical flow currentmeter.

An important requirement for currentmeters is to operate unattended in a marine environment for weeks at a time. The failure rate of SRCM's under these conditions is high. Generally, reliability increases with a decrease in the number of moving parts, especially moving parts in contact with the sea water. The rotor and vane of the SRCM are subject to fouling and "freezing". The internal mechanisms required by the rotor and vane also add problems. The EMCM has no external moving parts, however, it does have electrodes which must be in electrical contact with the sea water. It is possible that these electrodes could become corroded. The internal moving parts of the EMCM are two gimbal-mounted flux gate magnetometers and a tilt-meter. The LDCM has no external moving parts; its internal moving parts are the beam splitter, the grating, a compass and a tilt-meter.

The LDCM could be easily manufactured to withstand shipboard handling.

Its absence of external moving parts is an asset. The required transparent ports could be small in diameter and thick. Small "ruggedised" lasers for field work are available. The optical components could be assembled into modular units. Although the scattering volume results of Section 2 were based on the assumption of diffraction-limited optical components, the results presented in Section 2 were obtained using cheap low-quality lenses and the cylinder was made of moulded plexiglass; thus, the use of expensive diffraction-limited lenses and optical quality ports is not necessary. The essentially simple form of the photodector output means that the signal processing electronics can be minimal.

A disadvantage of the LDCM is the relatively high power required to operate the laser. The rotation of the beam splitter and radial grating could be accomplished by motors with power consumption smaller than the conventional recorder motor. The lifetime of a LDCM could be increased by intermittent rather than continuous operation. Improvements in batteries and laser efficiencies can be expected.

Preliminary estimates indicate that the cost of the LDCM could compare favorably with other meters.

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