J. Fluid Mech. (1972), *vol.* 56, *part* 1, *pp.* 143–160
Printed in Great Britain

Laser anemometry: a report on EUROMECH 36

By F. DURST,† A. MELLING AND J. H. WHITELAW
Department of Mechanical Engineering, Imperial College, London

(Received 20 July 1972)

1. Introduction

The 36th European Mechanics Colloquium (EUROMECH 36) which was held at Imperial College from 17 to 19 April 1972 was the first to be devoted to laser anemometry. It brought together European researchers whose primary interests included physics, electronics and fluid mechanics with the following purposes.

(i) To communicate theoretical knowledge of laser anemometry and, thus, to improve the general understanding of the principles of laser anemometry.

(ii) To exchange experience of the use of laser anemometers and, thereby, to establish optimum experimental procedures, based on the development of appropriate optical and data-processing systems.

(iii) To demonstrate the contributions which laser anemometry has made to fluid mechanics, particularly in turbulence research, and to assess its potential for further applications.

(iv) To establish the status of development of laser anemometry in Europe.

The Colloquium was attended by sixty-one research workers from eleven countries. Twenty-nine papers‡ were delivered and a further nineteen presentations were made in Open Forum sessions. The Open Forum sessions also allowed spontaneous comment and discussion on the various contributions.

The programme was divided under four subject headings and the more important findings are reviewed in the third part of this report. This is preceded by a review of laser anemometry which indicates the documented state of knowledge prior to the Colloquium. Previous reviews have been provided, for example, by Angus *et al.* (1969) and Schwar & Weinberg (1969), and that provided here is limited to describing significant developments and, in particular, those which have been published in the past few years. The report concludes with a section which summarizes the contributions which stem from the Colloquium and add to the understanding and application of laser anemometry.

2. Development of laser anemometry

The development of laser anemometry has called for contributions from and cooperation between research workers in a diversity of fields including branches of physics, electronics and fluid mechanics. The fundamental concept of a frequency shift in radiation received from a moving body by a stationary detector has been

† Present address; Sonderforschungsbereich 80, University of Karlsruhe.

‡ Abstracts of these papers are contained in a Colloquium booklet which is available from the last named author on request.

understood, and used in communications and astronomy, for example, for many years. The equation connecting the measured frequency difference $\Delta\nu$ to the instantaneous velocity can be derived from consideration of the Doppler shift of scattered radiation or from fringe considerations. It has the form

$$\Delta\nu = 2(\nu_S/C)\hat{U}\sin\phi$$

and expresses a linear relationship between $\Delta\nu$ and the instantaneous velocity $\hat{U}$. ν_S is the source frequency, ϕ the half-angle between the beams, and C the velocity of light. The linear relationship between $\Delta\nu$ and $\hat{U}$ is particularly encouraging since, in contrast to the hot-wire anemometer, the laser anemometer does not require calibration, and accurate measurement at high turbulence intensities is not complicated by nonlinear characteristics.

The research effort in laser anemometry has thus been directed towards applying a familiar principle in a new way using coherent light sources. The first application to fluid mechanics was described by Yeh & Cummins (1964), who measured velocity in a fully developed laminar pipe flow of water. Progress has subsequently been made on many aspects of the subject. Among these are the analysis and design of new and improved optical geometries, the development of pre-aligned optical systems readily adaptable to different flow situations, design of signal-processing equipment specifically suited to handling laser-Doppler signals, and the use of laser anemometers to measure in flow situations inaccessible to other instruments. Recent work in all these areas was reported during the Colloquium.

The remainder of this section is divided into three parts which consider, respectively, optical arrangements, signal-processing systems and light-scattering particles.

Optical arrangements

The most commonly used optical arrangements employ the 'reference-beam' or 'fringe' modes; a third arrangement, the 'single-beam' mode, has not been used as extensively as the others. The three modes are shown diagrammatically on figure 1. In the reference-beam or 'local oscillator heterodyning' mode, the laser beam is split into an intense scattering beam and a weak reference beam. The reference beam is directed onto a photocathode, where it beats with light scattered from the strong beam by particles moving with the flow: the scattered light undergoes a Doppler frequency shift. This arrangement was employed in the pioneer work of Yeh & Cummins (1964) and has subsequently been used by many authors. Goldstein & Hagen (1967), Welch & Tomme (1967) and Pike, Jackson, Bourke & Page (1968) applied it to turbulent water flow and Huffaker, Fuller & Lawrence (1969) and Lewis, Foreman, Watson & Thornton (1968) to turbulent air flow. More recently, it has been applied to a wider range of flow configurations, and among these may be cited the laminar, oscillatory water flow measurements of Denison & Stevenson (1970), the blood-flow investigations of Goldstein & Kreid (1971), the passage of a shock wave through water studied by Anderson, Edlund & Vanzant (1971) and the supersonic-flow investigations of Jackson & Paul (1971).

The fringe or 'dual scatter' system uses two intersecting beams of equal

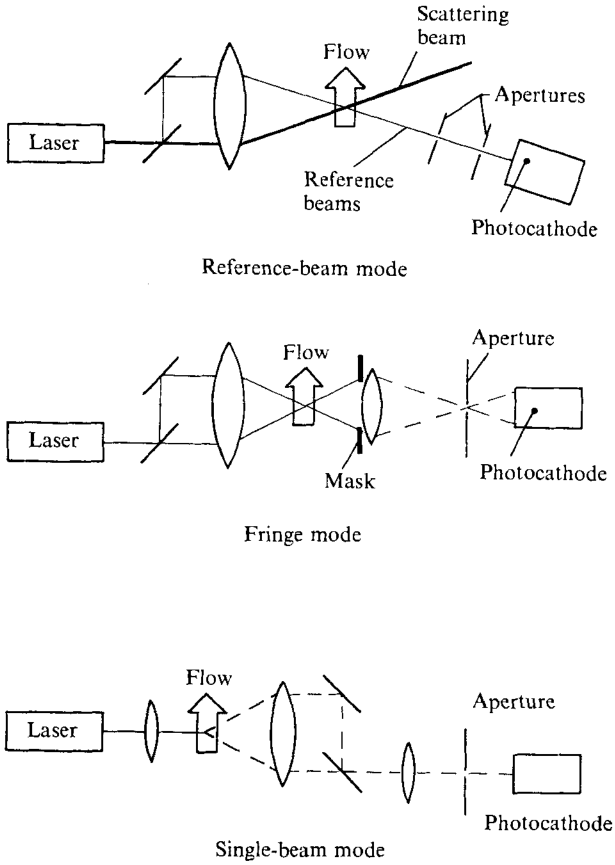


FIGURE 1. Optical arrangements.

intensity to produce a real fringe system. As each particle crosses the fringes, the intensity of light scattered onto the photodetector rises and falls at a rate directly proportional to the velocity. It has been used, for example, by Durst & Whitelaw (1971*a*, *b*) to measure mean and fluctuating velocity components in fully developed channel flow of water and in an axisymmetric air jet; by Rudd (1972) in his investigations of drag reduction by polymer addition; by Lennert, Trolinger & Smith (1972) to investigate vortices shed from aircraft wings; and by vom Stein & Pfeifer (1972) to measure the velocity relaxation of micron-sized particles in shock waves. Blake & Jespersen (1972) have also applied the fringe system to air jets in order to provide accurate calibration of impact probes and applications to combustion systems have been reported by Durst, Melling & Whitelaw (1972*a*, *b*), Durão, Durst & Whitelaw (1972) and Baker, Bourke & Whitelaw (1971).

The third optical arrangement, the single-beam or 'interferential Doppler' mode, has been discussed by Mazumder & Wankum (1970), Durst & Whitelaw (1971*c*) and Mazumder (1972). A single focused laser beam is directed into the flow and light scattered by a particle in two directions is collected symmetrically about the system axis. When the scattered beams are combined, the relative phase of their wave fronts depends on the distances of the particle from each light-collecting aperture; hence as the particle moves across the beam the scattered light beams interfere constructively and destructively leading to a light intensity at the photocathode which fluctuates at the Doppler frequency. This system offers no clear advantage over the fringe mode other than its use in measuring simultaneously two velocity components by collecting pairs of scattered beams in mutually perpendicular planes. The topic of aperture broadening of the Doppler signal spectrum resulting from the finite solid angle of a converging beam has been discussed in these references. In general aperture broadening has to be considered for both the transmitting and collecting optics, but some advantages of the one- and two-beam modes over the reference-beam mode have been suggested.

Analyses of the optical arrangements referred to as 'reference-beam' and 'fringe' modes have been presented, for example, by Durst & Whitelaw (1971*c*), who showed that the evaluation equations are identical. Drain (1972) demonstrated theoretically the relative advantages of the two arrangements. For some time it had been realized that the reference-beam mode could give rise to improved signal quality in particle-dense fluids and that the fringe mode was to be preferred in particle-rare fluids. Drain demonstrated that this was related to the design of the light-collecting arrangement, which, for the reference-beam mode, should contain a small aperture arranged to allow only coherent light waves to reach the photocathode, while for the fringe mode a much larger aperture can be used and is limited only by requirements of spatial resolution.

No distinction has yet been made between forward- and backward-scattering optical arrangements. The three geometries discussed above can all be employed with either forward- or backward-scattered light, but most measurements to date have employed forward scattering as this is very much more intense for scattering particles of the size normally used. Certain situations, however, may preclude the collection of forward-scattered light, and examples of measurements obtained with back-scattered light can be found in the papers of Bourquin & Shigemoto (1968) and Greated (1971).

To optimize the optical signal, the light source and the optical arrangement must be matched to each other and to the measuring system. The paper by Drain provides the criteria for the choice of optical mode but the choice of components and their specific dimensions must be determined. Comments on unequal light path lengths are provided by Foreman (1967) and on some fringe-mode optimization criteria by Lading (1971*a*) but the reader is referred to the contributions of Iten, Eliasson & Dandliker (1971) and of Durst & Whitelaw (1971*a*, 1972) for design criteria. Calculations comparing both forward and backward scattering for the same flow have been provided by Meyers (1971).

The value of integrated optical units has been mooted by, for example, Mayo (1970), Durst & Whitelaw (1971*a*) and Brayton, Kalb & Crosswy (1972). All of these units provide the possibility of accurate alignment in one optical mode and some provide the possibility of achieving this alignment with each of the three modes in forward and backward scatter. Such units permit laser anemometry to be used by those with little optical experience, and in environments less favourable than those normally to be found in laboratories.

Signal-processing systems

The optical signal is transformed into an electrical signal using a photodetector acting as a square-law detector. Important features of this electrical signal may be identified with the aid of figure 2 (plate 1), which shows two signal forms obtained in an air jet with a correctly designed and aligned optical arrangement. One signal form corresponds to a highly seeded flow with many light-scattering particles present simultaneously in the measuring control volume, i.e. more than 10^{11} particles/m^3 for a volume of 0·03 mm^3; the second signal form corresponds to a lower particle concentration, i.e. approximately 10^{10} particles/m^3.

The signals contain both amplitude and frequency modulation and carry wide-band noise: the required velocity information is, however, available only in the FM component. If the optical arrangement has been correctly aligned, the frequency of the FM signal, corresponding to each envelope, is directly proportional to the instantaneous velocity. When more than one particle is present at a time, the shape of the envelope depends on the relative phases of their Doppler signals. The depth of modulation is influenced by the relative beam intensities, the particle size and the alignment. The amplitude of the envelopes is influenced by particle size, the path followed by a particle through the control volume (which has a non-uniform light intensity) and the particle velocity (faster particles scatter fewer photons owing to their shorter residence time). The task of a signal-processing system is, therefore, to extract the frequency information from signal forms such as those shown on figure 2.

A problem confronting the analysis of Doppler signals is posed by contributions to the frequency modulation originating in sources other than turbulence of the flow; these are commonly called (non-turbulent) 'broadening' because of their influence on the probability-density distribution of the signal. Broadening contributions can arise from the finite lifetime of the signal from a given particle, velocity gradients within the measuring volume, the Gaussian intensity distribution across a laser beam, the presence of more than one particle in the measuring volume and the signal-processing equipment itself. Where they cannot be eliminated from the signal the demodulated output of the processor must be corrected for their presence.

Work on the development of signal-processing systems has recently received a great deal of attention as was made clear by Iten's contribution to the Colloquium. Early measurements were made with readily available spectrum analysers by means of which the probability-density distribution of the Doppler signal at a given point in the flow can be recorded. To determine the spectrum reliably requires that a large number of particles must be observed as the analyser sweeps across the frequency range of interest, and this necessitates a long time to acquire data on each point. Intrinsically the spectrum contains information on the mean frequency, and mean-square and higher order statistical correlations of the frequency fluctuations; the evaluation requires, however, that the spectrum be corrected for broadening unconnected with turbulent fluctuations. Spectrum analysis does possess the advantage that the sweeping filter automatically provides a good signal improvement for each centre frequency: it will, of course, include noise frequencies in its analysis. Comments on the interpretation of the Doppler spectrum can be found, for example, in Adrian & Goldstein (1971).

Frequency trackers are very much more convenient and rapid to operate; versions have been developed by, for example, Fridman, Huffaker & Kinnard (1968), Deighton & Sayle (1971), Mazumder (1972), Wilmshurst (1972) and Iten & Mastner (1971). These instruments provide instantaneous frequency-to-voltage conversion with an improved signal-to-noise ratio. With the exception of the instruments of Fridman, Huffaker & Kinnard and Iten & Mastner those referenced above are limited to maximum centre frequencies less than 15 MHz and, therefore, to low velocities, except when the turbulence intensity is so low that the Doppler frequency can be electronically shifted down to suit the tracker range.

Frequency trackers provide a continuous output signal but this advantage has a corresponding disadvantage in that a continuous input signal is required. In many flow configurations, low particle concentrations preclude continuous signals and electronic control devices are required if trackers are to retain the 'on-line' advantage. Devices of this type have been developed but no investigation of their performance has, so far, been published. Where computing facilities are available, either on line or via magnetic tape, the computer can be programmed to recognize the 'drop out' periods and to process the signal accordingly. The dynamic range of trackers limits their tracking ability to instantaneous frequency deviations of around 75 % of the mean or turbulence levels near 25 %. The papers by Huffaker (1970), Durst & Whitelaw (1971*a, b, c*), Bourke, Drain & Moss (1971), Durst, Melling & Whitelaw (1972*a, b*) and Durão, Durst & Whitelaw (1972) describe the application of frequency trackers.

The Fabry–Perot etalon used, for example, by James, Babcock & Seifert (1968) and Jackson & Paul (1971) can be arranged to track the optical signal directly. This procedure has not been applied, to date, and is likely to be limited to Mach numbers in excess of 0·5.

Means of timing the period of the Doppler signal have recently received attention from Blake & Jespersen (1972) and Brayton, Kalb & Crosswy (1972). Although this is the fundamental method for determining a frequency, difficulties in applying the technique arise owing to the amplitude modulation of the signal, and from noise. A delayed trigger is employed to initiate the timing process once a signal burst has been detected, and some form of logic circuitry is frequently incorporated to reject false counts. Period timing methods are able to work at high turbulence intensities in particle-rare situations, but do require a good signal-to-noise ratio as the signal enhancement provided by the narrow filters in the spectrum analyser and frequency tracker is not available.

A problem common to all methods of signal analysis is posed by reverse flow, as found in regions of high turbulence intensity. Since the Doppler frequency does not reflect the direction of flow in a given line, the Doppler frequency spectrum corresponding to a velocity spectrum overlapping zero velocity will be distorted in order to preserve all frequencies positive. To avoid this difficulty, optical frequency shifting devices are needed to change the frequency of one beam and so displace the Doppler frequency corresponding to zero velocity from zero to a finite positive value. A rotating grating has been used for this purpose by Denison & Stevenson (1970); the operation of a Bragg cell has been shown by Cummins & Knable (1963) but devices with a higher efficiency are required for application in laser anemometry.

All methods of signal analysis require that measured r.m.s. values be corrected for broadening of the Doppler spectrum attributable to sources other than turbulent velocity fluctuations. Some sources of broadening, and, therefore, of possible error to r.m.s. quantities have been discussed in the literature. For example, George & Lumley (1971) have discussed the problem of transit-time broadening and, although initially overestimating its significance, have made clear its origin and paved the way for its minimization. Related information has been provided by Edwards *et al.* (1971) and Adrian & Goldstein (1971). As indicated previously, discussions of aperture broadening and amplitude broadening in counting procedures have also been published. The subject has not, however, been exhaustively examined and no clear specification for the minimization and evaluation of errors is available. The papers by George & Lumley (1971), Iten, Eliasson & Dandliker (1971) and Durst & Whitelaw (1972) provide useful guidelines and the comparisons of optical anemometry measurements with exact solutions and hot-wire anemometry measurements, for example, those of Goldstein & Kreid (1971), Huffaker, Fuller & Lawrence (1969), Durst & Whitelaw (1971*a*, *b*) and Bourke, Brown & Drain (1971), indicate that precise corrections can be made to account for broadening. These papers indicate that it is possible to measure mean velocity, r.m.s. fluctuating components and Reynolds shear stress to precisions of 0·5 %, 2 % and 5 % provided that appropriate precautions are taken; it should be noted that these figures apply to relatively simple flows and to laboratory conditions.

It is useful to note that the procedure for applying a broadening correction is to subtract the mean-square frequency spread attributable to sources other than turbulence from the measured mean-square value. This statement applies to frequency analysis and to tracking procedures and appears to be appropriate to all forms of broadening.

Light-scattering particles

Although the presence of particles in the fluid under investigation is essential to laser anemometry, there is little published information relating specifically to this application. Texts on aerosols such as Green & Lane (1964) and Davies (1966) are of value but the only report which considers specifically the behaviour and specification of particles for laser anemometry is that of Melling (1971). General guidelines on the suitable size of scattering particles and the desirable concentrations of seeding are known; recommendations have also been made (Durst & Whitelaw 1972) for adjusting the optical system for optimum response to a given particle diameter and refractive index. However, particles are not readily obtained in uniform size and information on the refractive index is frequently lacking, so that analyses provide only qualitative guidance. Water normally contains an ample concentration of suitable particles without seeding but atmospheric air and gases usually do not.

3. Presentations at EUROMECH 36

The EUROMECH 36 Colloquium contained contributions relevant to almost all of the topics of the previous section. A summary of the presentations follows in four parts corresponding to the four main subject headings of the Colloquium. The first three parts are related to those of the previous section and the fourth was devoted specifically to applications.

Principles and practice of optical systems

The importance attached to the design and arrangement of optical components was demonstrated by the thirteen contributions to the session on "Principles and practice of optical systems". The subject was opened by the review lecture of L. E. Drain, in which the basic principles of reference-beam and two-beam (fringe) anemometers were considered. It was made clear that optical systems could be theoretically treated on the basis of either Doppler-shift or fringe considerations. Later in the session, B. Lehmann described an experiment which established the equivalence of the models. The static fringe pattern at the intersection region of two beams was suppressed by using beams polarized in mutually perpendicular planes; the polarized components of the scattered light were separated and then recombined with the same polarization and the Doppler frequency recovered. Drain also summarized his theoretical investigations of two-beam anemometers and showed that there are two different contributions to the mean-square signal which he calls the 'coherent' and 'non-coherent' contributions. This terminology was suggested as a classification of optical anemometers. It was concluded that the two-beam anemometer gives the best signals in flows of low particle concentration whereas reference-beam techniques are to be preferred if the particle concentration is high or if the intensity of background light is high. Drain indicated that the type of light-collecting system used should be selected according to whether coherent or non-coherent contributions to the signal were the more important.

Theoretical and experimental investigations of scattering phenomena were presented by F. Durst. He calculated the azimuthal intensity distribution of light scattered by spherical particles illuminated by several plane, linearly polarized, coherent light beams and used this to compute the azimuthal distributions of signal quality, signal strength and local signal-to-noise ratio. The direction dependence of the signal-to-noise ratio and the influence of the particle size relative to the fringe spacing on the signal strength showed that individual components of an optical anemometer must be matched to one another and to the flow configuration in order to achieve optimum signal quality and precision of measurement.

A detailed theoretical study of laser anemometers was presented by B. Eliasson, who took account of the Gaussian intensity distribution in laser beams and the actual positions of the optical components relative to each other and to the waist of the laser beam. His derivations of the optical-signal frequency indicate the need to locate the focusing lens at the focal distance from the laser light source in order to avoid a dependence of this frequency on the position of scattering particles within the control volume; this would contribute an additional broadening to the Doppler signal spectrum. Eliasson's analysis also considered particle concentration and, on the basis of signal-to-noise ratio computations, confirmed the differences between reference-beam and two-beam anemometers. These results are in accord with the theoretical findings of Drain and again point to the advantages of integrated optical units some of which can readily be adapted to operate in either manner.

The value of integrated optical units was made clear by several contributors to the session. H. J. Raterink described an integrated system which employs a holographically produced optical grating to split the laser beam. This optical arrangement can be used in the reference-beam and fringe mode and has a special attachment to permit back-scattering measurements: it also permits light-frequency shifting by several kHz. J. H. Whitelaw reported on the development of integrated optical systems which employ mirror-beam splitter arrangements to divide or combine the light beams. Two-channel optical units are able to measure mutually perpendicular velocity components simultaneously, and all models can be used for forward- and backward-scattering measurements. The latest version of these units includes a compensator to ensure equal light path lengths for each beam, to allow high-power lasers of short coherence length to be employed. J. E. Rizzo described a portable optical system which is an adaptation of the Mach–Zehnder interferometer. The ease of alignment of this instrument was stressed and stems from the fact that visible fringes are produced. Some doubts were raised as to its rigidity and alignment stability.

A 'noise-cancelling' optical anemometer was described by G. E. A. Meier. This employs polarized light with two photodetectors to observe the separate signals. The photodetector outputs are subtracted to eliminate the d.c. component of the signal and enhance the a.c. component due to the existing phase difference between the two signals. The extension to multi-directional simultaneous velocity measurements is imminent.

Considerations of the signal-to-noise ratio were presented by Lading and revealed that the optimum optical configuration for the fringe mode requires two beams of equal intensity, crossing in the measuring control volume, with the direction of detection along the bisector of the two beams. Considerations relating to photodetectors indicated that photodiodes may have application even with low-power lasers.

The application of optical anemometers to reversed or highly turbulent flow requires the incorporation of optical frequency shifting devices. R. J. Baker gave a summary of existing methods and their comparative features. The rotating diffraction grating is cheap but inefficient and limited to moderate frequency shifts. Acousto–optic devices have to be operated at frequencies over 30 MHz to give high efficiency, and Baker favoured the use of two electro-optic modulators both to split the laser beam and shift one portion of it. A. Müller described a technique which relates the velocity direction to the sign of the phase difference produced between two heterodyne signals when scattered light from each of two incident beams is combined. It would be interesting to see the method put to the test in an operating system.

A simple optical anemometer design based on the earlier work of Thompson (1968) was outlined by Tanner. The laser beam is split and focused to two high intensity foci about 5 μm diameter and 1 mm apart, and the velocity of a particle is determined simply from the time between its crossing the two foci. Although the system is unsuitable for turbulence measurements, the high intensity of light obtained by focusing permits mean-velocity measurements in unseeded air.

Principles and practice of signal analysis

The first of twelve contributions to the topic of signal analysis was a review lecture by P. D. Iten, who summarized basic principles of existing electronic data-processing systems operating both in the frequency and time domain. Three specific systems were discussed, namely a gated zero-crossing detector, a tracking receiver and a sampling f.m. demodulator. Their application to flow and vibration problems was described. The possibility of controlling the dimensions of the measuring control volume by amplitude discrimination of the optical signal was proposed: this implies the use of information from the centre of the control volume, where the light intensity is high.

M. O. Deighton discussed the theoretical design of frequency-tracking demodulators with particular reference to the DISA 55L20 instrument. A fixed-frequency filter, in combination with a voltage controlled oscillator in a superheterodyne feedback loop, is used to track the signal and provide good signal/noise improvement. Deighton showed the need for careful matching of the time constants of various components in the feedback loop in order to ensure stability and minimal over-shoot of the transient response. These requirements inevitably lead to a restriction in the tracking speed, which can be increased only at the expense of a deterioration of precision.

A comparison of hot-film and laser anemometry measurements was reported by Greated. Mean and r.m.s. values of one velocity component were measured in the flow behind a grid located in a water channel. The optical signals were analysed using a tracking demodulator; the resulting r.m.s. turbulence intensity measurements agreed with hot-film measurements within approximately 10 % and were more consistent.

A number of facets of signal analysis were considered by J. Oldengarm. By accounting for the random arrival of particles in the measuring control volume he developed a model for the influence of particle density, i.e. the fraction of time which particles are present in the control volume, on the measurement of turbulence power-density spectrum. He also suggested that the ambiguity-noise spectrum be separated from the turbulence power-density spectrum by examining the autocorrelation function of the demodulated signal. Oldengarm indicated that parameters such as the signal duration, particle density, and bandwidth of the ambiguity noise signal can be derived from the drop-out signal of a tracker such as the one described by Raterink.

Test results of a phase-locked loop tracker were reported by A. Melling. Using simulated and real Doppler signals, spikes in the demodulated output were shown to arise from the random initial phase of the signal bursts. A comparison of mean and r.m.s. fluctuation measurements obtained in a turbulent channel flow of water with the phase-locked tracker and a prototype of the DISA frequency-locked tracker indicated agreement of the mean velocity to within 2 % and of the axial r.m.s. velocity component to within 5 %.

The Open Forum on signal analysis led to the discussion of different data-processing systems. D. Jackson indicated the advantages and simplicity of Fabry–Perot etalons for use in high-speed flows. Period-timing device based on the timing of zero crossings within a signal burst from a single particle were described by both A. Smart and H. vom Stein; the latter instrument incorporated a logic circuit which rejected information when the average of N consecutive periods in a signal burst was significantly different from that for $2N$ consecutive periods in the same burst. A potentially useful instrument for testing signal-processing instruments is a signal simulator developed by T. H. Wilmshurst. This produces signals which are statistically identical to those from optical anemometers. Wilmshurst also described an autodyne tracking filter which yields an amplitude-weighted frequency. A. J. Hughes introduced an autocorrelation instrument which is particularly suited to processing Doppler signals constituted from a very small number of photons per cycle.

The possibility of errors arising in the measured Doppler frequency when two or more particles are simultaneously present inside the measuring control volume was discussed by J. C. Hoelgaard. Because of the random phase relationship of Doppler signals from different particles, the number of zero crossings of the combined signal from two particles with the same velocity could exceed by one the number of crossings from one particle, over the same interval of time.

Principles and practice of particle production and measurement

The seeding of air flows, with a sufficient concentration of contaminant particles to permit turbulence measurements over a short time interval, was reviewed by A. Melling, for the case where the motion of the suspended particles accurately represents the movement of the fluid. Analyses of particle response to turbulent fluid motion impose an upper limit of diameter of around 1 μm for typical particles in air but the generation and dispersal of such small particles causes difficulties. Techniques which have been tried include condensation of a vapour, pressure atomization, chemical reaction and fluidization of powders. Methods to measure the mean diameter of particles so produced are generally unsuitable for use outside specialist laboratories when applied to this size range.

The Open Forum was introduced by F. Durst, who described the design of pressure atomizers which have been used for velocity measurements in water sprays, and atomizers used to seed air flows and flames with silicone oil droplets.

Several speakers had used scattering particles for high-speed flows. H. vom Stein referred to measurements in which particles were accelerated by a shock wave from rest to about 200 m/s with an average acceleration of several million g; seeding particles of diameter below 1 μm were found to follow the flow very closely. A pressure atomizer capable of large flow rates was described by W. J. Yanta, who had used it to atomize water for measurements in a supersonic flow; the addition of dodecanol to the water inhibited evaporation of the droplets by forming a monolayer around them. A very simple means of seeding a supersonic flow was mentioned by D. Jackson, who had used ice particles formed in the wind tunnel as humid air expanded through a sonic nozzle: the size of these ice particles is, however, unknown.

Solid particles have been used by M. Philbert in air flows. $20\,\mu$m glass balls and $1\,\mu$m marble particles were dispersed by an ingenious apparatus designed to minimize agglomeration, but considerable aggregation undoubtedly took place. One of the difficulties of measuring in two-phase (liquid–gas) flows by optical means was discussed by W. Riebold, who indicated that the light is scattered from voids which are orders of magnitude larger than scattering particles suspended in the liquid phase.

An optical method for sizing particles was described earlier in the Colloquium by A. R. Jones. His method depends on determining the relationship between the signal strength and the ratio of particle size to fringe spacing; while the technique is satisfactory for uniformly sized particles refinements are required if the method is to be of use for poly-dispersed aerosols.

The application of optical anemometers

The introductory lecture to this session was presented by F. Durst, who emphasized the need for careful selection of optical components and choice of optical-system dimensions to optimize the optical signal. He stressed the value and adaptability of integrated optical units, illustrating their use in such widely different situations as blood flow and a diffusion flame. It was also shown that the appropriate signal-processing electronics depends on the particle concentration and turbulence intensity. An approximate analytic expression was provided to estimate the laser power necessary to provide a given signal-to-noise ratio in a given flow situation.

K. A. Blake described a fringe anemometer with signal analysis by period timing of the Doppler signal to permit operation in unseeded air flows. The system was designed for the calibration of pressure-based flow meters and, therefore, only required the measurement of mean velocity; however, developments are in hand to allow turbulence measurements. The use of a complete DISA optical system and tracking unit for measurements in a confined oil jet was outlined by B. Griverus. Measurements in supersonic flow had been carried out by W. J. Yanta. As expected, particles moving through an oblique shock wave did not respond immediately to the velocity change but their velocity recovered downstream to a value in agreement with compressible-flow calculations. With a knowledge of the particle size, the particle velocity lag can be computed and measurements by laser anemometry can be corrected to give the actual fluid velocity.

Remote measurement of air speed was the subject of talks by A. B. Gillespie and A. J. Hughes. Gillespie described a fringe system with back scattering capable of measuring wind speeds between 2·5 and 50 m/s at ranges up to 50 m using a 1 W argon-ion laser. Signals were processed with a bank of resonant filters, either in real time, by choosing the most resonant filter, or by time averaging to build up a Doppler-frequency probability-density distribution. The arrangement used by Hughes employed a 5 W CO_2 laser in a reference-beam configuration with heterodyning of the incident and scattered radiation in the laser cavity. The Doppler signal was processed in a frequency tracker and velocities up to 10 m/s were measured at a range of 200 m.

M. Philbert and A. Boutier earlier in the Colloquium discussed the combined use of photographic techniques and laser anemometry in order to locate the trajectory of particles injected into a flow, and then to measure their velocity. Both techniques revealed a substantial velocity lag for 20 μm marble particles in an air stream at 160 m/s and showed a dispersion in both magnitude and direction of the velocity because of particle size variations.

Bubbly air–water pipe-flow measurements described by W. Riebold made use of an optical correlation between fluctuations in the light transmitted from two parallel or crossed beams separated by a small axial distance. By detecting the leading and trailing flanks of the square wave formed by a passing bubble, the average bubble dimension, as well as its velocity, could be evaluated.

P. Testa & M. Viti had recorded the instantaneous level of a free liquid surface on a film from the trace produced by a laser beam directed vertically downwards through the surface; the method provides a remarkably simple way of monitoring small changes in level, but complications arise when foam forms on the surface.

In the Open Forum, R. J. Goldstein reported on measurements by laser anemometry in blood flows. To reduce the opacity of the blood, most of the haemoglobin was removed from the red corpuscles without changing their shape or size. Profiles were taken in plane ducts as narrow as 0·41 mm using a measuring volume of approximately 11 μm diameter. Two talks were concerned with velocity measurements in flames. R. J. Baker discussed initial experiences with laser anemometry in a 2 m industrial furnace with gas, coal and oil flames at temperatures up to 1700 °K; partial success was obtained with oil flames, but with gas flames there were too few particles to allow measurements and in the coal flame there were too many large particles. D. Durão described work on a laminar methane diffusion flame seeded with silicone oil; using a prototype DISA frequency tracker, periodic low frequency pulsations of the flow were observed.

The analytical basis for the application of laser anemometry to measurement of spatial correlation functions was presented at the Colloquium by Bertolotti: relevant information is provided in the papers by Bertolotti *et al.* (1971) and Di Porto, Crosignani & Bertolotti (1969).

4. Concluding remarks

The Colloquium revealed that a considerable amount of development work on laser anemometry is presently in progress in Europe; most of this is directed towards optical and signal-processing problems. The development of ingenious and efficient optical arrangements is continuing in some places, while at others the preference has been to choose one of the well-established geometries and put it to use. It is worth noting that, while research prior to 1970 was mostly made with some form of the reference-beam system, the symmetrical dual-scatter fringe arrangement has lately found increasing favour particularly because of its comparative ease of alignment. It will be interesting to see whether the technical advantages of some of the more complex systems will be sufficient to overcome their operational inconvenience.

There is growing awareness that no single signal-processing instrument will suit all the flow situations in which laser anemometers can be employed. Although spectrum analysis was used for all the early measurements in laser anemometry, it has been largely superseded by more convenient instruments; however, it remains a very useful diagnostic tool and is still used in flows such as industrial flames where the Doppler signal is of poor quality. Electronic frequency tracking demodulators permit much more rapid data acquisition, but they have been satisfactorily tested only in those flows with particle concentrations sufficiently high to allow continuity of signal. The frequency trackers discussed at the Colloquium were limited to a maximum frequency of 15 MHz corresponding to a velocity of the order of 30 m/s. On the other hand, possible optical tracking filters appear to be restricted to high velocities, e.g. Mach numbers greater than 0·5. The development of period timing instruments has been more recent, and much work remains to be done; such instruments offer many potential advantages in flows with low particle concentrations.

The evaluation of turbulence quantities from Doppler signals is complicated by broadening of the signal spectrum by non-turbulent effects. An informal discussion on broadening at the Colloquium showed that one obstacle to understanding the phenomena has been the confusion arising from the description of the same form of broadening in apparently different ways. Corrections for transit-time broadening and velocity-gradient broadening can be calculated, while Gaussian beam broadening can be eliminated by appropriate location of optical components relative to the beam waist. Broadening of the Doppler spectrum by the signal processing and noise must be quantified from measurements in a laminar flow. A clear exposition of successful methods to apply these corrections to actual data would be a useful contribution to the literature.

In spite of the efforts described in the previous sections, the number of reported measurements of fluid-dynamic significance is small. This undoubtedly stems, in part, from the multi-disciplinary nature of the subject, which requires a knowledge of optics, electronics, data processing and fluid dynamics. It is clear that important fluid-dynamic measurements have been made with optical anemometers but a greater effort in this direction is required. Among the fluid-dynamic questions which remain to be answered is that posed during the Colloquium by J. B. Wills; namely, can the laser anemometer measure turbulence power spectra more completely than hot-wire instrumentation?† To date no satisfactory spectral measurements have been obtained by laser anemometry; indeed, its reliability for measuring simpler quantities, such as second-order correlations, is not yet firmly established. It is likely, therefore, that the laser and hot-wire anemometer will be complementary techniques over the next few years.

† *Footnote added in proof*: In a paper recently received, J. W. Dunning & N. S. Berman (*N.A.S.A.* TMX-67969) appear to have satisfactorily measured power spectra in fully developed pipe flow.

REFERENCES

(An asterisk by a name indicates a lecture given at the Colloquium.)

ADRIAN, R. J. & GOLDSTEIN, R. J. 1971 Analysis of a laser-Doppler anemometer. *J. Phys.* E, *Sci. Instrum.* **4**, 505.

ANDERSON, R. E., EDLUND, C. E. & VANZANT, B. W. 1971 Measurement of particle velocity at a shock front in water with a laser-Doppler meter. *J. Appl. Phys.* **42**, 2741.

ANGUS, J. C., MORROW, D. L., DUNNING, J. W. & FRENCH, M. J. 1969 Motion measurement by laser-Doppler techniques. *Ind. Engng Chem.* **61** (2), 9.

BAKER, R. J.* Optical frequency shifting devices for directionally sensitive laser-Doppler anemometers.

BAKER, R. J., BOURKE, P. J. & WHITELAW, J. H. 1971 Measurements of instantaneous velocity in laminar and turbulent diffusion flames using an optical anemometer. *Imperial College, Mech. Engng Dept. Rep.* ET/TN/A/11 (to be published in *J. Inst. Fuel*).

BERTOLOTTI, M., CROSIGNANI, B., DAINO, B. & DI PORTO, P. 1971 The possibility of measuring spatial velocity correlation functions in a turbulent fluid by means of light scattering. *J. Phys.* A **4**, L47.

BLAKE, K. A.* The NEL laser velocimeter.

BLAKE, K. A. & JESPERSON, K. I. 1972 The NEL laser velocimeter. *NEL Rep.* no. 510.

BOSSEL, H. H., HILLER, W. J. & MEIER, G. E. A.* Noise cancelling, self-aligning optical anemometers for multi-dimensional velocity measurements.

BOSSEL, H. H., HILLER, W. J. & MEIER, G. E. A. 1972*a* Noise-cancelling signal difference method for optical velocity measurements. *J. Phys.* E, *Sci. Instrum.* to be published.

BOSSEL, H. H., HILLER, W. J. & MEIER, G. E. A. 1972*b* Self-aligning comparison beam methods for one-, two- and three-dimensional optical velocity measurements. *J. Phys.* E, *Sci. Instrum.* to be published.

BOURKE, P. J., BROWN, C. G. & DRAIN, L. E. 1971 Measurements of Reynolds shear stress in water by laser anemometry. *DISA Inf.* **12**, 21.

BOURKE, P. J., DRAIN, L. E. & MOSS, B. C. 1971 Measurements of spatial and temporal correlations of turbulence in water by laser anemometry. *DISA Inf.* **12**, 17.

BOURQUIN, K. R. & SHIGEMOTO, F. H. 1968 Investigation of air velocity by laser backscatter. *N.A.S.A. Tech. Note*, D-4453.

BOUTIER, A.* Design of an interferential velocimeter; application to gas and liquid flows.

BRAYTON, D. B., KALB, H. T. & CROSSWY, F. L. 1972 A two-component, dual-scatter laser-Doppler velocimeter with frequency burst signal readout. *A.E.D.C. Rep.* (submitted to *Appl. Optics*).

CUMMINS, H. Z. & KNABLE, N. 1963 Single sideband modulation of coherent light by Bragg reflexion from acoustical waves. *Proc. I.E.E.E.* **51**, 1246.

DAVIES, C. N. 1966 *Aerosol Science*. Academic.

DEIGHTON, M. O.* Design principles of a frequency tracker for laser anemometry.

DEIGHTON, M. O. & SAYLE, E. A. 1971 An electronic tracker for the continuous measurement of Doppler frequency from a laser anemometer. *DISA Inf.* **12**, 5.

DENISON, E. B. & STEVENSON, W. H. 1970 Oscillatory flow measurements with a directionally sensitive laser velocimeter. *Rev. Sci. Instrum.* **41**, 1475.

DENISON, E. B., STEVENSON, W. H. & FOX, R. W. 1971 Pulsating laminar flow measurements with a directionally sensitive laser velocimeter. *A.I.Ch.E. J.* **17**, 781.

DI PORTO, P., CROSIGNANI, B. & BERTOLOTTI, M. 1969 Statistical properties of light scattered by particles suspended in a turbulent fluid. *J. Appl. Phys.* **40**, 5083.

DRAIN, L. E.* Principles and practice of optical systems.

DRAIN, L. E. 1972 Coherent and noncoherent methods in Doppler optical beat velocity measurement. *J. Phys.* D **5**, 481.

Durão, D.* Optical measurements of instantaneous velocity in diffusion flames.

Durão, D., Durst, F. & Whitelaw, J. H. 1972 Optical measurements in a pulsating flame. *Imperial College, Mech. Engng Dept. Rep.* ET/TN/A/14.

Durst, F.* Scattering phenomena and their application in optical anemometry.

Durst, F.* The application of optical anemometers.

Durst, F., Melling, A. & Whitelaw, J. H. 1972*a* The application of optical anemometry to measurement in combustion systems. *Comb. & Flame*, **18**, 197.

Durst, F., Melling, A. & Whitelaw, J. H. 1972*b* Optical anemometer measurements in recirculating flows and flames. *DISA Conf. on Fluid Dyn. Measurements in Indust. & Medical Environments. Paper*, II. 2–2.

Durst, F. & Whitelaw, J. H. 1971*a* Integrated optical units for laser anemometry. *J. Phys.* E, *Sci. Instrum.* **4**, 804.

Durst, F. & Whitelaw, J. H. 1971*b* Measurements of mean velocity, fluctuating velocity, and shear stress using a single channel anemometer. *DISA Inf.* **12**, 11.

Durst, F. & Whitelaw, J. H. 1971*c* Optimization of optical anemometers. *Proc. Roy. Soc.* A**324**, 157.

Durst, F. & Whitelaw, J. H. 1972 Theoretical considerations of significance to the design of optical anemometers. *Imperial College, Mech. Eng. Dept. Rep.* ET/TN/A/15.

Edwards, R. V., Angus, J. C., French, M. J. & Dunning, J. W. 1971 Spectral analysis of the signal from the laser-Doppler flowmeter: time-independent systems. *J. Appl. Phys.* **42**, 837.

Eliasson, B., Iten, P. & Dandliker, R.* Analysis of Doppler flowmeters.

Foreman, J. W. 1967 Optical path length difference effects in photomixing with multimode gas laser radiation. *Appl. Optics*, **6**, 821.

Fridman, J. D., Huffaker, R. M. & Kinnard, R. F. 1968 Laser-Doppler system measures three-dimensional velocity vector and turbulence. *Laser Focus*, **4**, 34.

Fristrom, R. M., Jones, A. R., Schwar, M. J. R. & Weinberg, F. J.* Particle sizing by interference fringes.

George, W. K. & Lumley, J. L. 1971 The measurement of turbulence using a laser-Doppler velocimeter. *I.S.A. Symp. on Flow. Paper*, no. 5-2-58 (Pittsburgh).

Gillespie, A. B.* The remote measurement of wind velocity and gustiness using back-scattered laser light.

Goldstein, R. J. & Hagen, W. F. 1967 Turbulent flow measurements utilizing the Doppler shift of scattered laser radiation. *Phys. Fluids*, **10**, 1349.

Goldstein, R. J. & Kreid, D. K. 1971 Measurement of velocity profiles in simulated blood by the laser-Doppler technique. *I.S.A. Symp. on Flow. Paper*, no. 4-2-95 (Pittsburgh).

Greated, C.* Comparison of laser and hot-film anemometers for the measurement of turbulence statistics.

Greated, C. 1971 Resolution and back-scattering optic geometry of laser-Doppler systems. *J. Phys.* E**4**, 585.

Green, H. L. & Lane, W. R. 1964 *Particulate Clouds: Dusts, Smokes, and Mists.* 2nd edn. London: E. & F. N. Spon.

Griverus, B.* Measurement of velocity distribution in a two-dimensional jet at small Reynolds number flow.

Huffaker, R. M. 1970 Laser-Doppler detection systems for gas velocity measurement. *Appl. Optics*, **9**, 1026.

Huffaker, R. M., Fuller, C. E. & Lawrence, T. R. 1969 Application of laser-Doppler velocity instrumentation to the measurement of jet turbulence. *S.A.E. Conference*, Detroit.

Hughes, A. J.* Long range anemometry using a CO_2 laser.

Hughes, A. J., Jones, R., Pike, E. R. & O'Shaughnessy, J. 1972 CO_2 laser anemometry in the atmosphere. *RRE Newsletter & Res. Rev.* **11**, paper 16.

HUGHES, A. J., OLIVER, C. J., PIKE, E. R. & O'SHAUGHNESSY, J. 1970 Measurement of wind velocity by laser scattering. *RRE Newsletter & Res. Rev.* **9**, paper 7.

ITEN, P. D.* Principles and practice of signal analysis.

ITEN, P. D., ELIASSON, B., DANDLIKER, R. 1971 Investigations and improvement of spectral and spatial resolution of a laser Doppler flowmeter. *IEEE/ISO Conference on Laser Engineering and Applications*, Washington (to be published in *Appl. Optics*).

ITEN, P. D. & MASTNER, J. 1971 A laser-Doppler velocimeter offering high spatial and temporal resolution. *Brown Boveri Res. Rep.* KLR-71-07.

JACKSON, D. A. & PAUL, D. M. 1971 Measurement of supersonic velocity and turbulence by laser anemometry. *J. Phys.* E, *Sci. Instrum.* **4**, 173.

JAMES, R. N., BABCOCK, W. R. & SEIFERT, H. S. 1968 A laser-Doppler technique for the measurement of particle velocity *A.I.A.A. J.* **6**, 160.

JONES, A. R.* See FRISTROM *et al.*

LADING, L.* Analysis of signal-to-noise ratio of a laser anemometer. (See also *RISØ N-Rep.* N-15-72.)

LADING, L. 1971*a* Differential Doppler heterodyning technique. *Appl. Optics*, **10**, 1943.

LADING, L. 1971*b* Two-phase flow measurements utilizing laser anemometry. *RISØ M-report.*

LEHMANN, B.* An experiment concerning the fringe-pattern model with regard to the two-beam dual-scatter method.

LEHMANN, B. 1968 Zur Diagnostik von Zweiphasen-strömungen II. *AER-Forschungs-institut*, **19**, 11039.

LENNERT, A. E., TROLINGER, J. D. & SMITH, F. H. 1972 Application of electro-optic techniques for jet and wake flow-field investigations. *A.E.D.C. Rep.*

LEWIS, R. D., FOREMAN, J. W., WATSON, H. J. & THORNTON, J. R. 1968 Laser-Doppler velocimeter for measuring flow-velocity fluctuations. *Phys. Fluids*, **11**, 433.

MAYO, W. T. 1970 Simplified laser-Doppler velocimeter optics. *J. Phys.* E, *Sci. Instrum.* **3**, 235.

MAZUMDER, M. K. 1972 A symmetrical laser-Doppler velocity meter and its application to turbulence characterization. *N.A.S.A. Contractor Rep.* no. 2031.

MAZUMDER, M. K. & WANKUM, D. L. 1970 SNR and spectral broadening in turbulence structure measurement using a CW laser. *Appl. Optics*, **9**, 633.

MEIER, G. E. A.* See BOSSEL *et al.*

MELLING, A.* Doppler signal analysis with a phase-locked loop demodulator.

MELLING, A.* Principles and practice of particle production and measurement.

MELLING, A. 1971 Scattering particles for laser anemometry in air: selection criteria and their realization. *Imperial College, Dept. Mech. Engng Rep.* ET/TN/B/7.

MEYERS, J. F. 1971 Investigation of basic parameters for the application of a laser-Doppler velocimeter. *A.I.A.A. Paper*, no. 71–288.

MÜLLER, A.* Measurement of the sign of a velocity component from the phase difference of the two heterodyne signals.

MÜLLER, A. 1970 Neue Elemente in der Technik der laser-Doppler Velocimeter. *Appl. Optics*, **9**, 2393.

OLDENGARM, J.* Processing of signals from a laser-Doppler velocimeter.

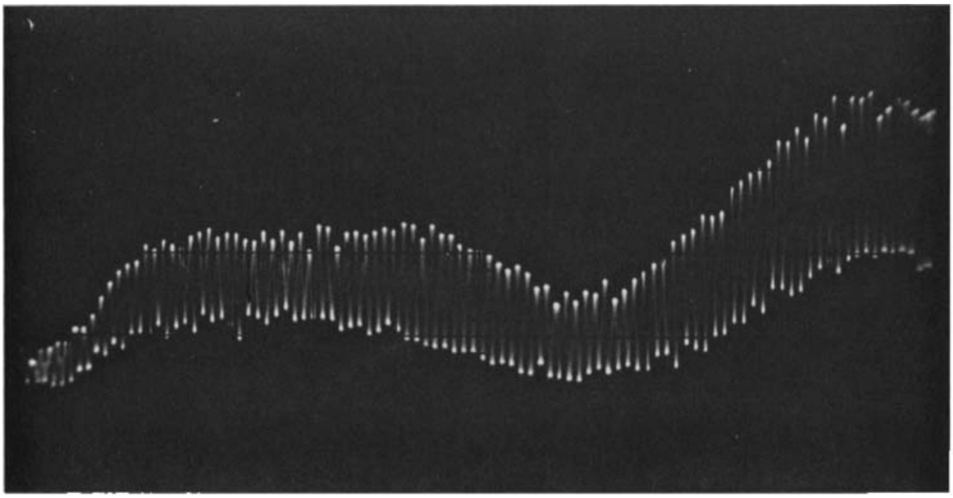
PHILBERT, M.* Particle velocity measurements by a photographic method using two pulsed lasers.

PIKE, E. R., JACKSON, D. A., BOURKE, P. J. & PAGE, D. I. 1968 Measurement of turbulent velocities from the Doppler shift in scattered laser light. *J. Phys.* E, *Sci. Instrum.* **1**, 111.

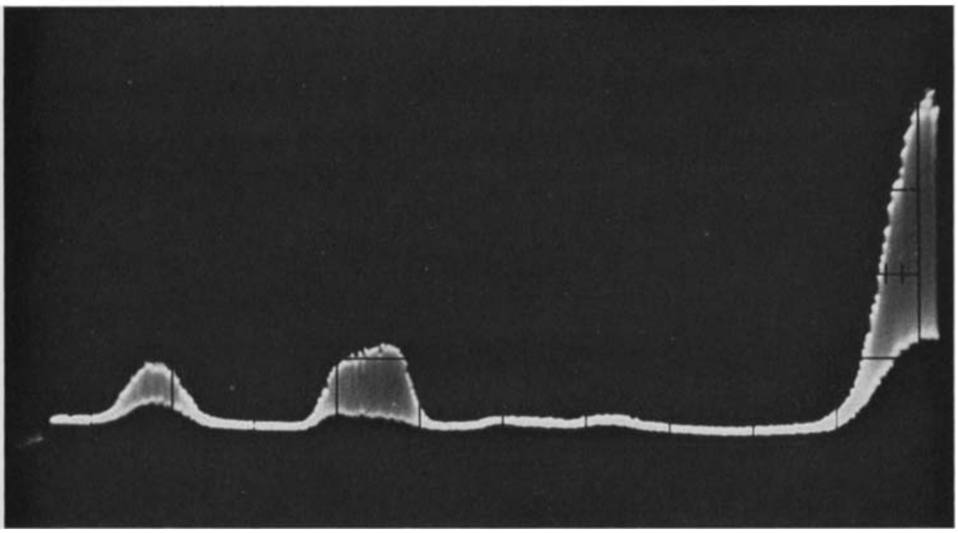
RATERINK, H. J.* Current development of a laser-Doppler anemometer at the Institute of Applied Physics TNO-TH.

RIEBOLD, W., MATTHES, W. & FRIZ, G.* Applications of correlation methods in two-phase flow investigations.

RIZZO, J. E.* A laser-Doppler interferometer.



(*a*)



(*b*)

FIGURE 2. Signal forms obtained in an air jet with a correctly aligned optical arrangement. (*a*) Highly seeded flow. (*b*) Lower concentration.

RUDD, M. J. 1972 Velocity measurements made with a laser doppler-meter on the turbulent pipe flow of a dilute polymer solution. *J. Fluid Mech.* **51**, 673.

SCHWAR, M. J. R. & WEINBERG, F. J. 1969 Laser techniques in combustion research. *Comb. & Flame*, **13**, 335.

TESTA, P. & VITI, M.* Measuring and recording of rapidly variable liquid levels by means of a laser beam.

THOMPSON, D. H. 1968 A tracer-particle fluid velocity meter incorporating a laser. *J. Phys.* E, *Sci. Instrum.* **1**, 929.

VOM STEIN, H. D. & PFEIFER, H. J. 1972 Investigation of the velocity relaxation of micron-sized particles in shock waves using laser radiation. *Appl. Optics*, **11**, 305.

WELCH, N. E. & TOMME, W. J. 1967 Analysis of turbulence from data obtained with a laser velocimeter. *A.I.A.A. Paper*, no. 67–179.

WHITELAW, J. H.* Integrated optical arrangements.

WILMSHURST, T. H.* A real-time Doppler signal simulator incorporating velocity modulation and an autodyne tracking filter.

WILMSHURST, T. H. 1972 An autodyne signal processor for laser-Doppler anemometry. Submitted to *J. Phys.* E, *Sci. Instrum.*

WILMSHURST, T. H., GREATED, C. & MANNING, R. 1971 A laser fluid-flow velocimeter of wide dynamic range. *J. Phys.* E, *Sci. Instrum.* **4**, 81.

YANTA, W. J. & GATES, D. F.* Laser-Doppler velocimeter measurements in supersonic flow.

YANTA, W. J., GATES, D. F. & BROWN, F. W. 1971 The use of a laser-Doppler velocimeter in supersonic flow. *A.I.A.A. Paper*, 71–287.

YEH, Y. & CUMMINS, H. Z. 1964 Localized flow measurements with an He–Ne laser spectrometer. *Appl. Phys. Lett.* **4**, 176.