

The Development of Multi-Point Laser Doppler Anemometry (MPLDA): A New Method to Estimate Fluid Flow Statistics

by

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ABSTRACT

In this paper we describe a method to measure fluid flow fields that we call Multi-Point Laser Doppler Anemometry (MPLDA). Like Doppler Global Velocimetry (DGV) and single point Laser Doppler Anemometry (LDA), the technique derives information from the Doppler shift observed when light is scattered from a moving particle and exploits the advantages of these techniques. The method retains the elegant simplicity of DGV, but uses coherent heterodyne detection as in LDA rather than applying an absorption edge to demodulate the Doppler signal (as in DGV). This makes MPLDA suitable for the measurement of flow fields throughout the velocity range. In contrast with pulsed laser imaging techniques, such as Particle Image Velocimetry (PIV) and its derivatives, MPLDA does not require individual seeding particles to be resolved as is the case with LDA and DGV. We believe that this makes MPLDA unique in its ability to gain whole field measurements in large scale, low speed wind tunnel facilities.

In essence MPLDA utilises a streak camera and coherent detection to record a short segments of the Doppler signals collected from many points within a seeded flow field. The streak image is then analysed to estimate the Doppler frequency at each point in the flow. In our original studies we used reflection from a galvanometer mirror to implement streak imaging. Using this technology we were able to prove the principles of MPLDA by measuring the surface velocity of a spinning disk. In this case the disk velocity was low (1/20 rev/sec) and consequently the measured Doppler frequencies were in the range of 0-10kHz. These initial results clearly demonstrated the potential of MPLDA, however, the scale and speed of the experiment are several orders of magnitude less than that which would be expected in a wind tunnel. In addition the reference beam necessary for coherent detection did not include a frequency shift and as such the measurements were subject to directional ambiguity.

More recently we have conducted investigations into the use of electronic vacuum tube technology as a means to implement the streak imaging requirement of MPLDA. A streak tube of this kind is similar in principle to an image intensifier and uses deflection plates to displace electrons en route to an output phosphor screen. In this way pico second resolution is possible. In what follows, a streak tube in conjunction with a Peltier cooled CCD camera is used to provide a flexible MPLDA streak system for both low and high speed wind tunnel facilities. We demonstrate the use of this system as a means to measure the velocity of spray particles within the measurement volume of a basic, single component, LDA system.

INTRODUCTION

Non-intrusive optical flow measurement techniques are vitally important in the study of fluid flow phenomena both to provide new insight into flow behaviour and increasingly, as a means to validate computational models. Single-point velocity measurements are commonly made using Laser Doppler Anemometry (LDA) (Durrani and Greated, 1977) while Particle Image Velocimetry (PIV) (Adrian 1991) is now an established method to make planar, two-component velocity measurements and stereoscopic (Lawson and Wu, 1999) and holographic techniques (Coupland and Halliwell, 1997) can be employed to make three-component measurements. More recently Doppler Global Velocimetry (DGV) has been demonstrated by Komine and Brosnan (1991) and has been refined and extended by Meyers (1995) and others to make planar three-component measurements in practice.

In order to perform quantitative comparisons with computational models, the choice of experimental technique is strongly influenced by the ability to collect sufficient data to characterise a given flow in a reasonable time. In this respect, the elegant simplicity of DGV is very appealing, particularly when three-component measurements are desired. The technique is also more appropriate to large-scale air flows than PIV since it is not necessary to identify individual particles in the flow and for this reason the increased scattering efficiency afforded by a fine seeding mist or smoke, rather than large (and heavy) particles, can be exploited. A major limitation of DGV remains however. Although the technique is relatively straightforward to implement in the study of high-speed (supersonic) flows, the need for a well stabilised laser source and SNR limitations of the sensor restrict the resolution of the technique to a few metres per second in practice (McKenzie 1996).

We have recently demonstrated a technique that is applicable throughout the velocity range 0 - 100km/s (Coupland 2000). The technique that we now call Multi-Point Laser Doppler Anemometry (MPLDA) retains much of the simplicity of DGV and derives velocity information from the Doppler shift associated with light scattered from a laser illuminated fluid flow. However, a stabilised source is not necessary since we implement coherent detection using a streak camera. In the following paper, we introduce MPLDA and describe our initial proof of principle experiments using a rotating mirror streak camera that allowed us to measure flows at a relatively small scale and small velocity. We then discuss a more robust and flexible implementation of MPLDA using a vacuum tube streak camera, which can be used for large scale studies throughout the velocity range.

THE MPLDA METHOD

The most general MPLDA geometry for three-component measurement of flow structure within a wind tunnel section is shown in figure 1. In essence, this geometry is similar to that proposed by Meyers (1995) for three-component, transonic DGV studies and consists of three CCD cameras (I,II and III). Cameras I and II view the flow from opposite directions whilst the third camera, III has an orthogonal view such that the optical axes of all the cameras lie in a single plane. The flow is illuminated with coherent light that propagates in a direction orthogonal to this plane. In traditional DGV this is usually in the form of a light sheet, however, for reasons which will become apparent, a set of parallel (not necessarily coplanar) propagating laser beams are preferred here.

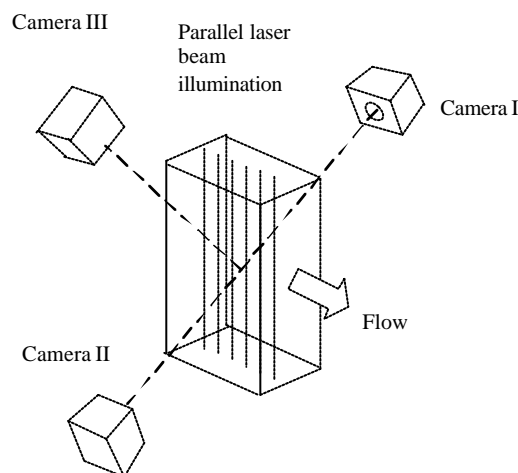


Fig. 1. MPLDA geometry

It is well known that if a particle moving with velocity, \mathbf{v} , is illuminated by a laser beam, the Doppler shift, Δn , observed in the scattered light is given by,

$$\Delta n = \frac{n(\hat{\mathbf{k}}_s - \hat{\mathbf{k}}_i) \cdot \mathbf{v}}{\lambda} \quad (1)$$

where n is the refractive index of the ambient fluid, λ , is the wavelength and, $\hat{\mathbf{k}}_s$ and $\hat{\mathbf{k}}_i$, are unit vectors in the direction of propagation of the scattered and illuminating fields respectively. Thus the Doppler shift is directly proportional to the velocity in the direction of the sensitivity vector, \mathbf{s} , defined by, $\mathbf{s} = n(\hat{\mathbf{k}}_s - \hat{\mathbf{k}}_i)/\lambda$. With reference to figure 1, it can be seen that at the point where the optical axes cross, $\mathbf{s}_I, \mathbf{s}_{II}$ and \mathbf{s}_{III} corresponding to the sensitivity vectors of each camera, are mutually orthogonal. Thus the Doppler shift in the light collected by each camera from this point is proportional to an orthogonal component of the fluid velocity.

Using the geometry discussed above, with $v=1\text{m/s}$, $\lambda=514\text{nm}$ and $n=1$, the Doppler shift is found to be approximately 3MHz and represents a frequency change of about 1 part in 2×10^8 . In practical, DGV instrumentation the Doppler shift is measured by comparing the intensity of an image recorded through an Iodine cell with that recorded without such a filter. The absorption edge of Iodine vapour has a bandwidth of approximately 400Mz and a gradient such that a 1% change in intensity transmittance is observed for a 10MHz excursion which corresponds to a velocity resolution of about 3.6m/s using the geometry of figure 1 at $\lambda=514\text{nm}$. It is clear that in order to achieve a measurement resolution approaching this value, the wavelength of the laser and the Iodine absorption line must be mutually stable. Although Roehle and Schodl (1994) have demonstrated a system of this kind, practical problems of camera alignment and detector noise remain. For this reason, it is unlikely that DGV using Iodine demodulation methods will find widespread application outside of transonic or supersonic flow studies.

Since it is the Doppler shift rather than the absolute frequency that is of interest, mixing the scattered light with a coherent reference wave provides a demodulation method which is insensitive to small changes in the source frequency. This method is the basis of single point laser Doppler anemometry (LDA) first proposed by Yeh and Cummins (1964) and is also used in Doppler Lidar systems for the remote measurement of atmospheric turbulence (Intrieri et. al., 1990) In order to employ coherent detection in simultaneous, whole field measurements, however, it is necessary to have an imaging detector of high bandwidth to record the temporal information necessary to resolve the Doppler shift.

The basis of MPLDA is to use streak cameras to record the Doppler signal (Doppler burst) scattered from points along the length of the laser beams. In essence a streak camera provides both spatial and temporal information by translating the time varying image across a stationary CCD detector. In this way, the intensity of the light scattered from a laser beam can be found as a function of time and if the scattered light is mixed with a reference wave then a periodic fluctuation in intensity is observed at the Doppler frequency. This is illustrated in figure 2.

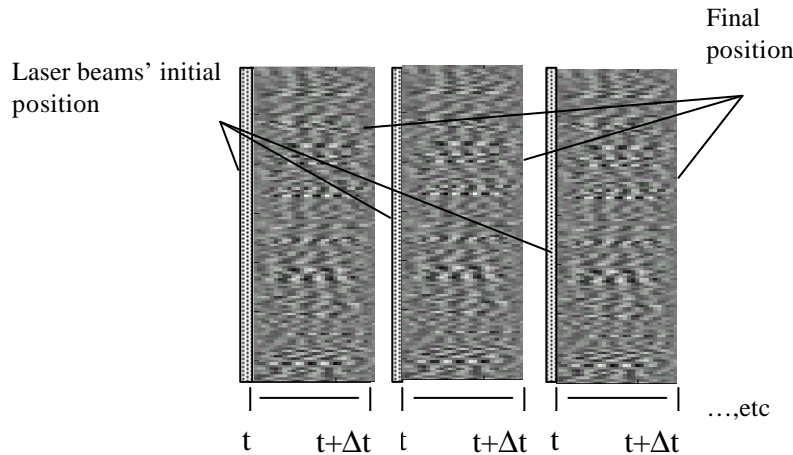


Fig. 2. Streak image

In this case the translation effected by the streak camera is in the horizontal direction and has been truncated such that a short burst of the time history can be seen for several laser beams that appear as vertical lines. Fourier transformation of each burst is then used to recover the mean Doppler frequency. The major advantage of MPLDA over PIV is that it is not necessary to identify individual particles in the image to make flow measurements. In conventional PIV the superposition of particle images results in a speckle pattern that is subject to de-correlation in the relatively long periods between exposures necessary to achieve a measurable displacement. For this reason PIV is inappropriate for many wind tunnel studies where the scale would necessitate seeding with prohibitively large and heavy particles to ensure adequate particle image exposures. In contrast MPLDA has the potential to work well with a fine seeding mist or smoke particles that are often used for flow visualisation in these facilities.

PRELIMINARY WORK

In our original work we used reflection from a galvanometer mirror to streak the image across a progressive scan CCD sensor (Coupland 2000). Initially, the configuration was used to measure the tangential velocity along a line through the centre of spinning disk as shown in figure 3.

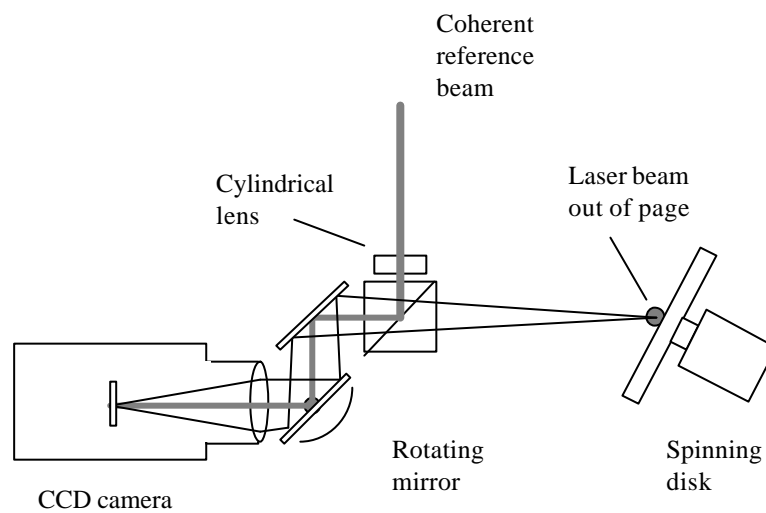


Fig. 3. Spinning disk configuration

The disk surface was illuminated at grazing incidence with a single laser beam of wavelength $\lambda = 532\text{nm}$ and approximately 0.25mm in diameter. The disk was driven by a signal generator at an angular velocity of 0.31 rad/sec (1/20 rev/sec) and the galvanometer mirror was driven with a triangular waveform at the camera frame rate of 25Hz. The amplitude was adjusted such that the angular excursion of the mirror was sufficient to produce a full width streak image 768 pixels in length giving an effective sampling rate of 38.4kHz. In this way a single streak was recorded in each frame. Figure 4 shows a typical streak image.

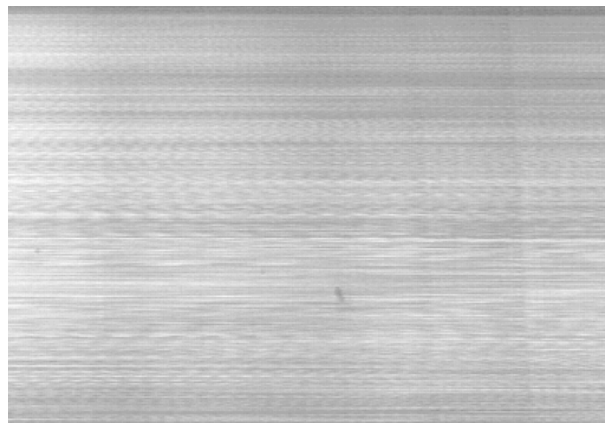


Fig. 4. Spinning disk streak image

Demodulation of this image was accomplished by one-dimensional power spectrum of each line in the image and scaling according to the effective sampling rate and the results are shown in figure 5. Finally, the Doppler shift was calculated by finding the positions of the dominant peaks in each line of figure 5 and from consideration of the geometry the magnitude of the disk velocity was calculated at each point using equation 1. Figure 6 shows the measured velocity along the laser beam (crosses) and its theoretical value (solid line). The small overestimate in velocity is attributed to an inaccuracy in the measurement geometry.

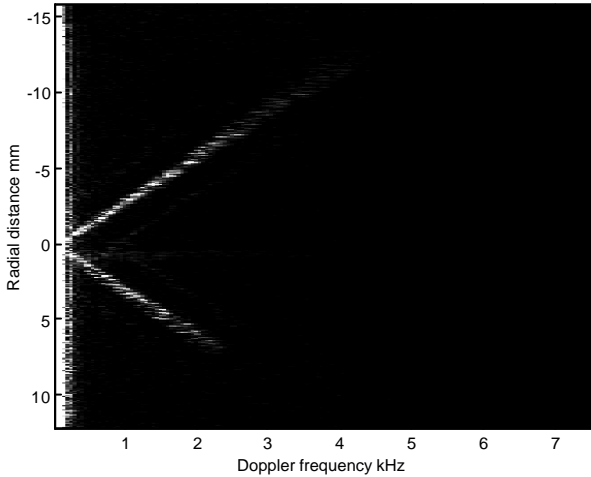


Fig. 5. Demodulated power spectra

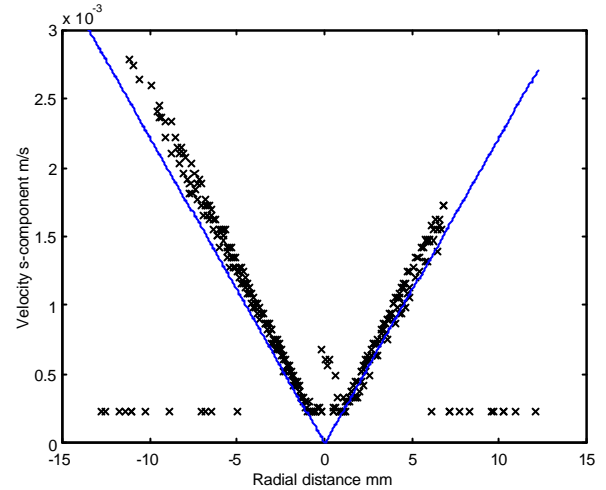


Fig.6. Measured (crosses) and theoretical (solid line) velocity

Although these results were encouraging, it is noted that the diameter of the disk (20mm) and the range of measured velocity ($< 3\text{mm/s}$) are both very small and are several orders of magnitude less than that expected in a practical flow measurement situation. In addition, it is noted that only the magnitude of the velocity has been measured and, like LDA, a frequency shift in the reference beam is necessary to resolve directional ambiguity. On the basis of these results it was decided to build new instrumentation capable of large scale work that can be used to measure flow velocities in a range typical of a subsonic wind tunnel (0.1-10m/s). This is described in the following section.

STREAK TUBE INSTRUMENTATION

Inspection of equation 1 shows that the maximum Doppler shift occurs in back-scatter geometry ($\hat{\mathbf{k}}_s = -\hat{\mathbf{k}}_i$) and at a velocity of 10m/s and wavelength of 532nm this corresponds to approximately 38MHz. Although it is possible to design a mechanical streak camera using rotating mirrors for example, that is capable of recording a signal of this frequency, it would require expensive specialist mechanics. A more flexible and cost effective approach is to use a streak tube based on vacuum tube technology (Johnson et. al 1980). This technology has been developed to investigate ultra-fast phenomena and is capable of pico-second resolution and with effectively no lower limit. Streak tube technology can therefore be configured to measure flow velocity from zero to over 100km/s!

Figure 7 shows a schematic of our streak camera. The streak tube used is a photochron 5 tube from Photek Ltd. The tube consists of a blue/green sensitive S25 photocathode, an image intensifier section with x-y deflection plates, and a fast response phosphor (1ms). The output image is relayed to a 12bit 1280x1024 Vosskuhler COOL-1300Q CCD array. With this arrangement we have shown that the streak camera is capable of recording events with a bandwidth in excess of 1GHz and an output frame rate of up to 12fps.

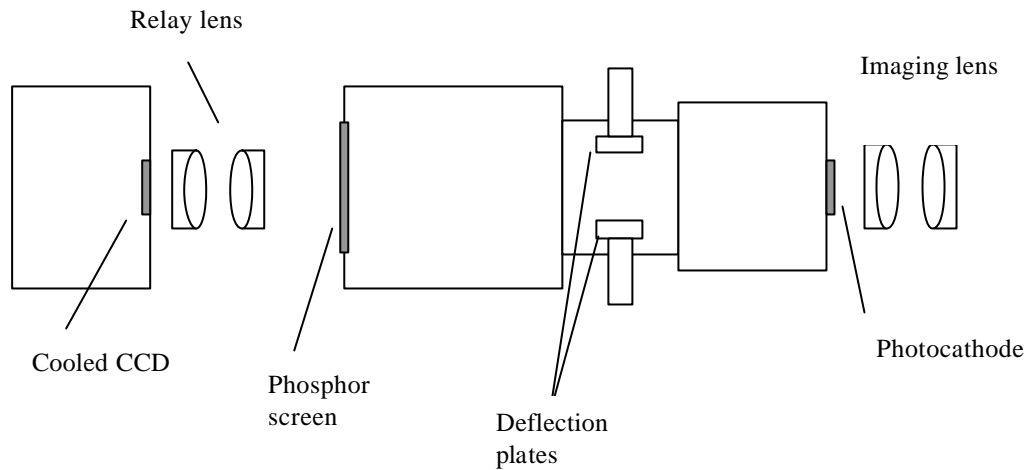


Fig. 7. Schematic of a vacuum tube streak camera

Due to late delivery of the streak tube we can only report our initial tests of the streak camera system. In these tests the streak camera was used to image the probe volume of a basic cross-beam LDA system as shown in figure 8. The LDA used a rotating diffraction grating to give a frequency shift of 1.4MHz. In this configuration the width of the probe volume and fringe frequency were approximately 125 μ m and 10 μ m respectively. The LDA operated at a wavelength of 532nm using Coherent Verdi laser at 500mW.

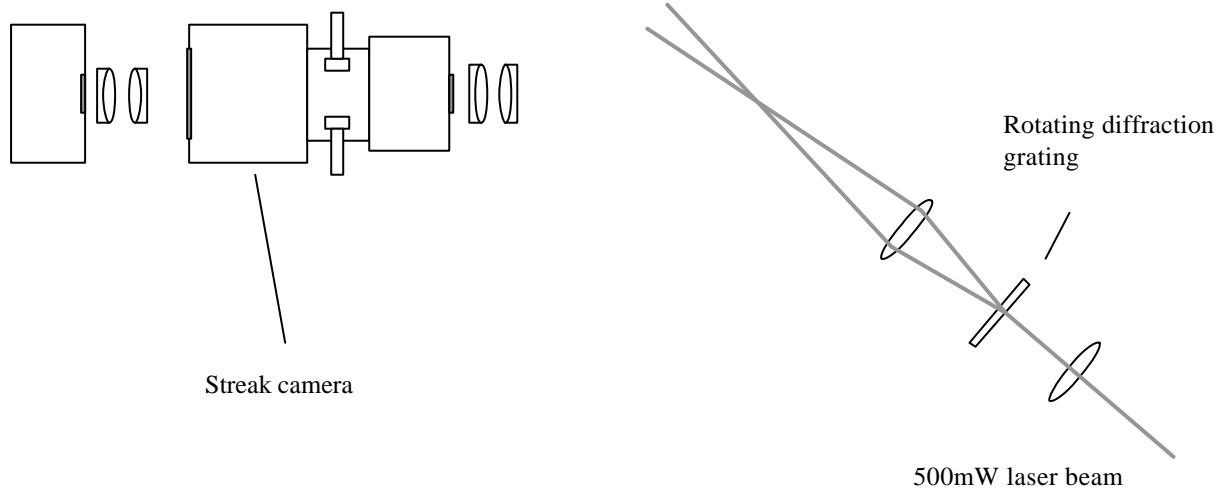
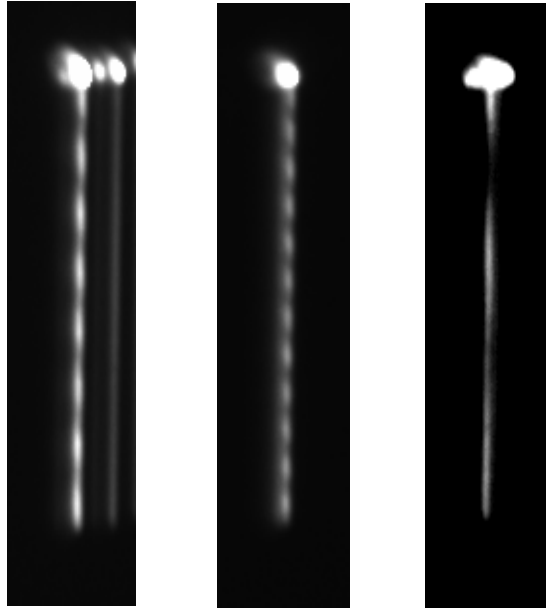


Fig. 8. Streak recording of cross-beam LDA

In these studies a water spray with an estimated drop size of 50 μ m was directed through the flow volume. Figure 9a)-c) show the streak images obtained approximately 1m from the probe volume using an F#1.4 16mm lens. Each streak is 10 μ s duration. Figure 9a) shows a spray particle travelling nominally parallel to the cross-beam fringes and shows the 1.4MHz reference frequency. Figures 9b) and c) show spray directed toward and away from the sensitivity vector respectively. It can be deduced that the spray velocity is approximately 9m/s.



*Fig. 9. Streak recording of cross-beam LDA with spray directed;
a) parallel to fringes b) along the sensitivity vector c) opposite to the sensitivity vector*

CONCLUSION

It is clear from the results presented in this paper that it is possible to construct an MPLDA system utilising streak imaging to record Doppler bursts from many points along the path of one or more laser beams. Mechanical systems using rotating mirrors can be used to implement streak imaging but electronic streak tube technology provides a more robust solution and a specification that makes it applicable to the measurement flow fields throughout the velocity range. Thus with picosecond streak periods, it may be possible to measure velocities up to 100 km/s. In the initial tests presented here, we have proved the MPLDA principle by measuring surface velocity of a low-speed inclined disk and we have also demonstrated the new streak tube technique by measuring a droplet spray at a more typical flow velocity by imaging a cross-beam LDA configuration through the streak tube camera. Our next objective is to build a full scale streak tube MPLDA system for use in a medium scale, sub-sonic wind tunnel.

REFERENCES

- Adrian R.J "Particle Imaging Techniques for Experimental Fluid Dynamics" *Annu. Rev. Fluid Mech.* 23 p261 (1991).
- Coupland. J.M., and Halliwell. N.A., "Holographic Displacement Measurements in Fluid and Solid Mechanics: Immunity to Aberrations by Optical Correlation Processing", *Proc. Roy. Soc.* 453 1053-1066 1997.
- Coupland J.M., "Coherent detection in Doppler global velocimetry: a simplified method to measure subsonic flow fields", *Applied Optics* 39(10), p1505-1510 (2000).
- Durrani TS and Greated CA, "Laser Systems for Flow Measurement" Plenum New York (1977)
- Intrieri, J.M., Bedard A.J., and Herdesty, R.M. "Details of Colliding Thunderstorm Outflows as Observed by Doppler Lidar" *J. Atmos. Sci.* 47 1081-1098 1990.
- Johnson, C.B., Nevin, S., Brebis, J., Abshire, J.B., "Circular-scan streak tube with solid-state readout" *Applied Optics* 19(20) p3491-3495 1980.
- Komine. H., and Brosnan., S.J., "Real Time Doppler Global Velocimetry" AIAA 29th Aerospace Sciences Meeting Reno N.V. paper 91-0337 1991.
- Lawson N.J., Wu J. "Three-Dimensional Particle Image Velocimetry: A low-cost 35mm angular stereoscopic system for liquid flows" *Optics and Lasers in Engineering* 32, p1-19 (1999).

- McKenzie, R.L. "Measurement Capabilities of Planar Doppler Velocimetry using Pulsed Lasers" *Appl. Opt.* 35 6 948-964 1996.
- Meyers, J.F. "Development of Doppler Global Velocimetry as a Flow Diagnostics Tool" *Meas. Sci. Technol.* 6 769-783 1995.
- Roehle, I., and Schodl, R., "Evaluation of the Accuracy of the Doppler Global Technique" Optical Methods and Data Processing in Heat and Fluid Flow conference, City University, London April 1994. p121-136 1994.
- Yeh, Y., and Cummins, H., "Localised Fluid Measurements with a HeNe Laser Spectrometer" *Appl. Phy. Lett.* 4 176-178 1964.