

# Single camera 3D planar velocity measurements using imaging fibre bundles and two frequency Planar Doppler Velocimetry (2v-PDV)

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## ABSTRACT

3D planar flow-field measurements are made using multiple imaging fibre bundles to port different views of the measurement plane, defined by a laser light sheet, to a CCD camera. The Doppler frequency shifts of particles entrained in the flow are transduced to intensity using an iodine absorption cell. Only a single CCD camera is used eliminating the pixel matching problem. Two optical frequencies generated from the same source are used sequentially to provide a reference and signal image.

**Keywords:** Planar Doppler Velocimetry, PDV, Doppler Global Velocimetry, DGV, acousto-optic modulators, imaging fibre bundles

## 1. INTRODUCTION

Planar Doppler Velocimetry (PDV)<sup>1,2</sup> is a flow measurement technique that provides velocity information over a plane defined by a laser light sheet. PDV relies upon measuring the Doppler frequency shift of light scattered from particles entrained in the flow. As PDV relies upon the Doppler shift a single observation direction can measure a single component of velocity, as shown in Figure 1. The use of imaging fibre bundles<sup>3</sup> allows several observation directions, and thus velocity components, to be measured simultaneously on different portions of the CCD.

The optical frequency shift,  $\Delta\nu$ , is given by the Doppler equation:

$$\Delta\nu = \frac{\nu(\hat{o} - \hat{i}) \cdot V}{c}$$

where  $\nu$  is the optical frequency,  $\hat{o}$  and  $\hat{i}$  are unit vectors in the observation and illumination directions respectively,  $V$  is the velocity vector and  $c$  is the free space speed of light. The optical frequency of light scattered from each particle in the seeded flow experiences a Doppler shift, which is linearly related to the velocity of the particle at that point in the flow. In PDV, a region of the illuminated flow is imaged, through a glass cell containing iodine vapour, onto the active area of a CCD camera. Iodine has numerous narrow absorption lines over a large part of the visible spectrum<sup>4</sup>. If the laser frequency is chosen to coincide with one such line, the optical intensity at any position in the camera image is a function of the Doppler shift experienced at the corresponding flow position, via the frequency-dependent iodine absorption.

The intensity over a PDV image is affected by the intensity profile of the illuminating laser sheet (typically Gaussian), spatial variations of the seeding density within the flow, and diffraction fringes caused by imperfections in the optical surfaces. These variations are generally of similar amplitude to those resulting from absorption in the iodine cell, and can obscure the information about flow velocity that is contained within the camera image. It is therefore usual to amplitude-divide the image beam onto two cameras; from one of the two imaging paths the iodine cell is omitted, and the resulting image acts as a reference to normalize the signal image carrying the velocity information. In the two-frequency planar Doppler velocimetry (2v-PDV)<sup>5</sup> technique the signal and reference images are acquired on the same CCD camera by the use of two illumination frequencies.

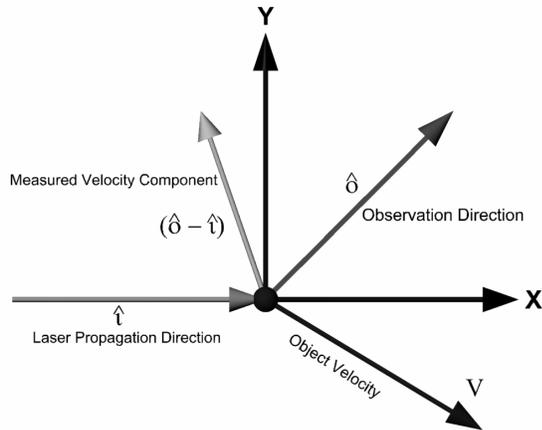


Fig 1. The relationship of laser illumination direction and observation direction to the measured velocity component determined from the Doppler equation.

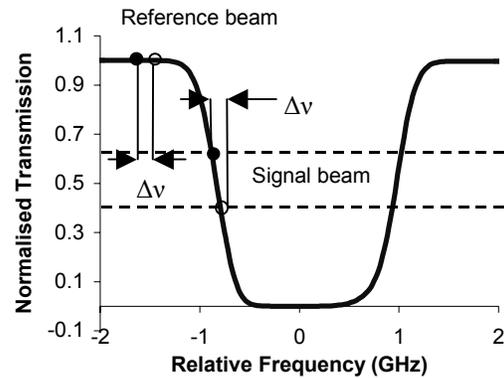


Fig 2. Relative positions of the laser frequency, and the shifted frequency on a typical absorption feature for 2v-PDV (Open circles denote the position of the illumination frequency and closed circles the Doppler shifted frequency.)

The emission wavelength of the laser is tuned just off the low frequency side of an absorption line. The output beam is first frequency up shifted to lie in a zero absorption region of the iodine transfer function. A reference image is then acquired. The frequency is then downshifted to lie approximately midway (50%) on the iodine cell transfer function, see figure 2, and a signal image is acquired. The optical frequency difference is  $\sim 700\text{MHz}$ , which is sufficiently small that there will be no change in the scattering for the size of particles typically used;  $0.2\text{-}5\ \mu\text{m}$  diameter. Exact alignment of the reference and signal images on the active area of the camera is automatic. The method also eliminates the polarization sensitivity of the split ratio of the beam splitter used in the two-camera system.

Without the use of the imaging fibre bundles, to port multiple views to a single detector head, it would be necessary to have three separate detector heads to measure 3 component velocities, one for each measured velocity component. Each of these would consist of two cameras and an iodine cell; however this is reduced to a single camera and iodine cell when using the two-frequency technique.

## 2. EXPERIMENTAL SETUP

A schematic of the experimental arrangement used in this work is shown in figure 3. A continuous wave argon ion laser was used as a light source, allowing time averaged velocity measurements to be made. The optical frequency of this light source was altered to form the reference and signal beams using a combination of two acousto-optic modulators. The generation of both the reference beam, where the frequency is downshifted by  $180\text{MHz}$ , and the signal beam, where the frequency is up shifted by  $520\text{MHz}$ , is shown in the detail of the two-frequency beam generator. Both beams leave the beam generator and are coupled into an optical fibre. The beams are then delivered to a prism-scanning device. This scans the collimated beam rapidly across the region of interest, resulting in an ideal 'top-hat' intensity profile of the generated light sheet. The desired illumination frequency can then be selected by toggling on/off the two AOMs. A frequency locking system is used to control the laser's fundamental frequency, and hence the positions of the two beams on the iodine absorption line. This consists of an iodine cell, signal and reference photodiodes and locking electronics which adjusts the laser etalon temperature to ensure that the laser frequency is stable, based upon the transmission through this cell. Views of the region of interest are ported to the detector head using a coherent array of fibres that is split into four channels. Each channel has  $600 \times 500$  fibres that are  $8\ \mu\text{m}$  in diameter and positioned at  $10\ \mu\text{m}$  centres. These views are combined at the detector head, with each occupying a quarter of the CCD image. An example of the image formed is shown in figure 4. This is a view of a calibration target used to de-warp the views to common view. Figure 5 shows the views after this de-warping process; all four views have been overlaid for demonstration purposes.

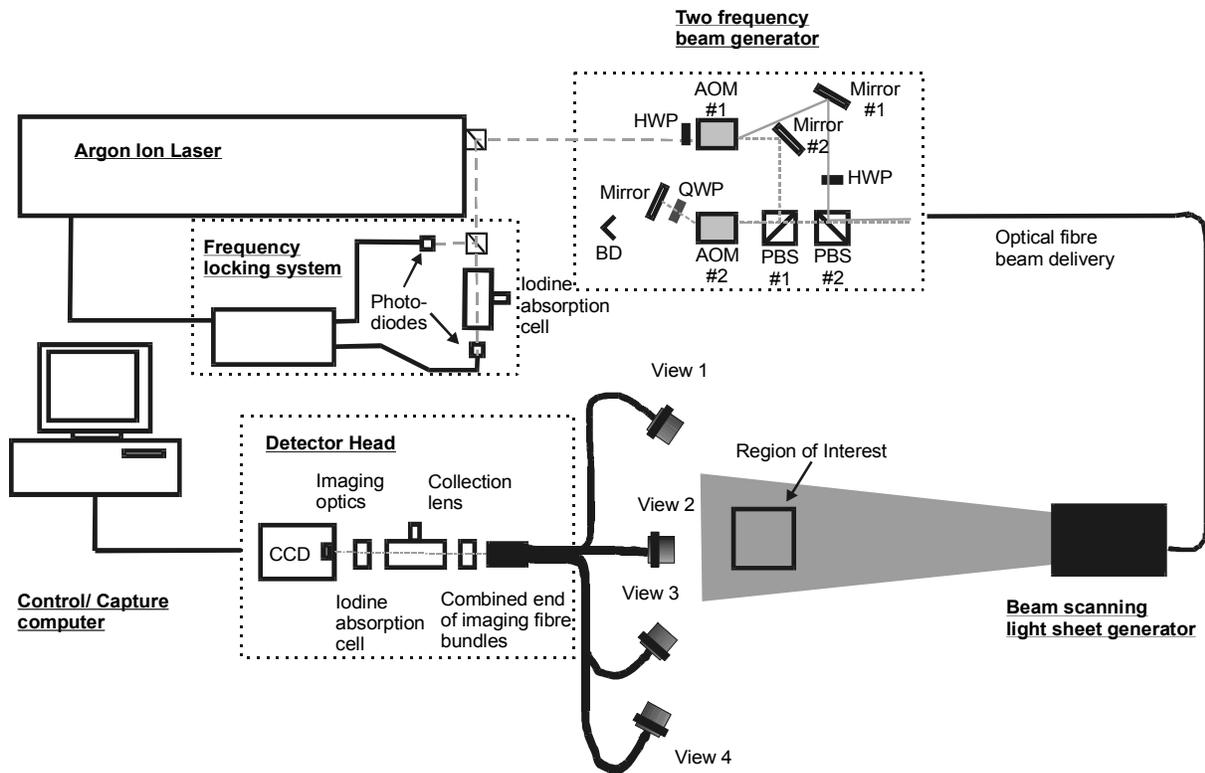


Fig. 3. Schematic showing the experimental arrangement; including detail of the two frequency beam generator showing the generation of both the signal and reference beams

HWP -  $\lambda/2$  plate; AOM – acousto-optic modulator; PBS – polarising beam splitter, QWP –  $\lambda/4$  plate; BD – beam dump.

———— Reference beam path    - - - - - Signal beam path    - - - - - Un-shifted laser beam

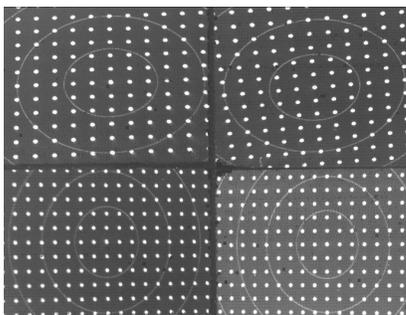


Fig. 4. An example image of a view through the imaging bundles of a calibration target

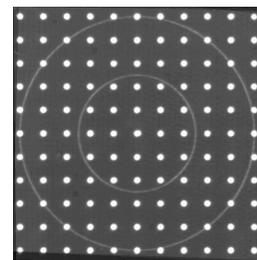


Fig. 5. An example of the 'de-warped' views. Showing all four views overlaid

### 3. RESULTS

The system was initially tested as a single velocity component system where the imaging fibre bundles were replaced by a camera lens, giving a single viewing direction. This was first used to make measurements on a rotating disc, which provides a well-known velocity field. It was then demonstrated on a seeded air jet to provide conditions similar to the techniques intended applications on seeded air flows<sup>5</sup>. Figure 6 shows the main velocity component of this jet at various positions from the nozzle. The system was then extended to measure three velocity components, using the imaging fibre bundles as the input into the detector head. The rotating disc was again used to characterise the performance of the system. Each arm of the imaging fibre bundle was used with a standard SLR camera lens to view the rotating disc. The disc itself was 200mm in diameter, although the common field of view of each observation direction was an approximate disc 100mm in diameter. The rotation of the disc was measured using an optical tachometer giving a maximum velocity

in the field of view of  $\sim 20\text{ms}^{-1}$ . Each of the observation directions was processed through to a velocity component, with the direction given by  $(\hat{\theta} - \hat{i})$ . An example of a typical component can be seen in figure 7(a). These measured velocity components are then converted to the orthogonal components aligned with the coordinate system of the experiment. Figures 7(b) and (c) show examples of these computed orthogonal velocity components, with the velocity changing from zero at the centre of the wheel to the maximum magnitude at the edges.

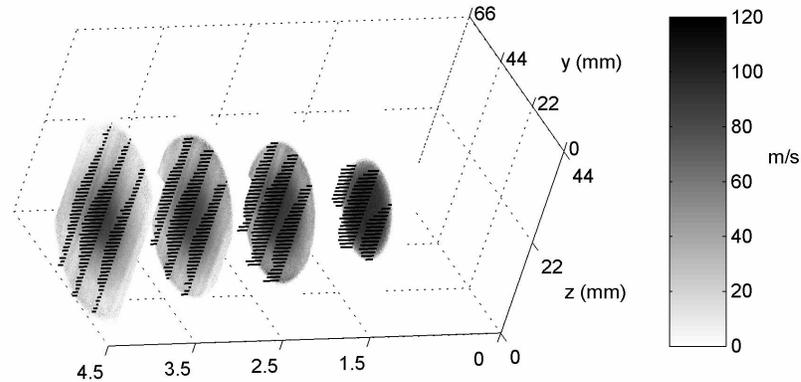


Fig. 6. The velocity field of an axisymmetric air jet made using 2v-PDV. Measurements were taken at 1.5, 2.5, 3.5 and 4.5 nozzle diameters downstream from the nozzle. Overlaid are vectors showing the magnitude of the velocity at various points (arrow heads have been removed for clarity)

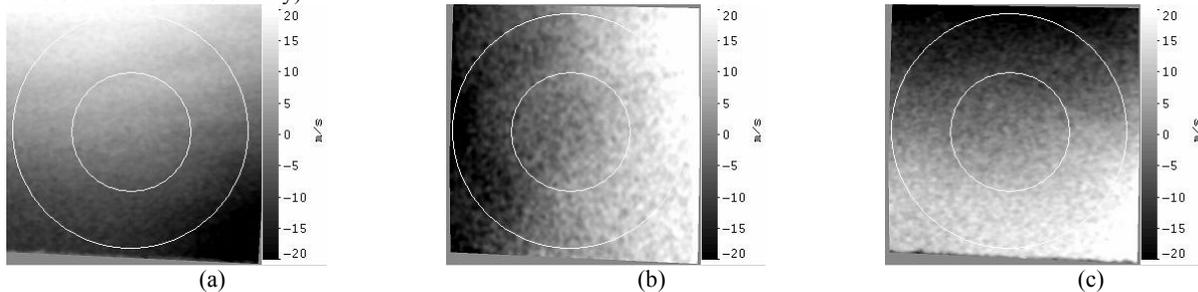


Fig. 7. Velocity fields from a rotating disc (a) An example of a processed velocity component. (b) Typical computed horizontal (U) velocity component. (c) Typical computed vertical (V) velocity component.

#### 4. CONCLUSIONS

A PDV technique using two illumination frequencies and imaging fibre bundles has been demonstrated that is capable of measuring all three components of velocity, across a plane defined by a light sheet, using *a single* CCD camera. The use of the imaging bundles also allows greater flexibility in the positioning of the observation directions and the two frequency approach uses only a single camera overcoming the pixel matching problem.

#### ACKNOWLEDGMENTS

This work was funded by an Engineering and Physical Sciences Research Council (EPSRC), UK (GR/SO4291).

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