

## Instantaneous Two-frequency Planar Doppler Velocimetry using pulsed Nd:YAG lasers

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**Abstract** Two-frequency Planar Doppler Velocimetry is a modified planar Doppler velocimetry (PDV) technique that uses sequential illumination of the flow using two illumination frequencies with the flow viewed through an iodine cell. The first illumination frequency is tuned to coincide with an iodine absorption line (typically at around 50% transmission) and the second is tuned to a full transmission frequency. An image captured under the first illumination frequency will have intensities related to the Doppler shift of the light scattered from particles seeded in the flow and provides a signal image. A second image captured with the second illumination frequency is insensitive to Doppler shifts and provides a reference image. This allows Doppler velocimetry measurements of the flow to be made using a single CCD camera and avoiding image misalignment issues associated with PDV.

The 2v-PDV technique has been previously demonstrated making time-averaged velocity measurements using a CW argon ion laser. This paper describes the extension of this work to allow instantaneous velocity measurements to be made using the 2v-PDV technique. A pulsed 2v-PDV system is described which uses two independently seeded Nd:YAG lasers to illuminate the flow with the two frequencies of light required. A CCD camera capable of capture two closely spaced images (~300ns) is used to capture the signal and reference images sequentially. As the time separation between the images is small the motion of the seed particles in the flow is effectively frozen. Preliminary results on the velocity field of a rotating disc and a seeded air jet are presented.

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### 1. Introduction

Planar Doppler Velocimetry (PDV) - Ford and Tatam (1997), Elliott and Beutner (1999), Nobes et al. (2004) - also known as Doppler Global Velocimetry (DGV) - Meyers and Komine (1991), Meyers (1995), Reinath (1997), Willert et al. (2005) - is a flow measurement technique that allows the measurement of velocity information over a plane defined by a laser light sheet. In PDV the velocity is determined by measuring the Doppler shift of light scattered from particles that have been seeded into the flow. A region of the illuminated flow is imaged, through a glass cell usually 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, Gerstenkorn and Luc (1986). The laser frequency is chosen to coincide with one such line and hence the optical intensity at any position in the camera image is a function of the Doppler shift experienced at the corresponding position in the flow, via the frequency-dependent iodine absorption.

However the intensity over a PDV image is affected by other factors such as the intensity profile of the illuminating laser sheet and spatial variations in the seeding density. To prevent these variations

obscuring the velocity information it is usual to amplitude-divide the image beam onto two cameras. In one imaging path the iodine cell is omitted and this image can be used as a reference to normalise the signal image.

The relationship between the Doppler frequency shift of the scattered light and the velocity of the scattering particle is given by the Doppler equation, here  $\nu$  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.

$$\Delta\nu = \frac{\nu(\hat{o} - \hat{i}) \cdot V}{c} \quad (1)$$

Viewing the flow from a single observation direction allows a single component of the flow velocity to be measured; therefore to make three-dimensional measurements a minimum of three viewing directions are necessary. Conventional methods use a separate PDV imaging head (two cameras and an iodine cell each) to measure each of the three velocity components. The use of imaging fibre bundles - Nobes et al. (2001), Nobes et al. (2004), Willert et al. (2005) - to port multiple views of the region of interest to a single detector head reduces the number of imaging heads needed and simplifies the system.

## 2. Two Frequency Planar Doppler Velocimetry

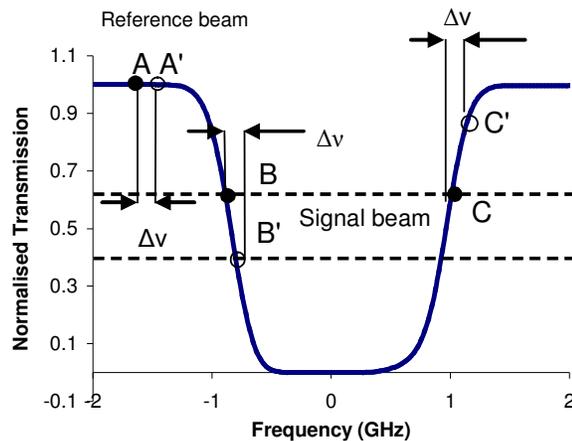
In two-frequency Planar Doppler Velocimetry (2v-PDV) - Ford et al. (2003), Charrett et al. (2004a), Charrett et al. (2004b), Charrett and Tatam (2006) - the signal and reference images are acquired sequentially on a single CCD camera, figure 2, by using two illumination frequencies, separated by ~1GHz and positioned at different positions on the iodine absorption line.

This overcomes several problems identified with conventional PDV. In conventional PDV superposition of the two images to sub-pixel accuracy is essential if errors in the calculated velocities are to be minimized. For example an image misalignment of 0.1 pixels gives an estimated error of  $\pm 5\text{ms}^{-1}$  when measuring the velocity field of a rotating disc - Thorpe et al. (1995). Errors due to poor image registration are particularly troublesome if large velocity gradients are present in the region imaged. In 2v-PDV alignment of the reference and signal images on the active area of the camera is no longer an issue and the signal/reference image misalignment problem found in conventional PDV is avoided.

The 2v-PDV method also eliminates the polarization sensitivity of the split ratio of the beam splitter used in two-camera systems. Ideally the beam splitter used in a conventional PDV imaging head

would split the incoming light 50:50 between the signal and reference cameras with no variation for different polarizations of light. However even the 'non-polarizing' beam splitters typically used retain a slight sensitivity to polarization, typically quoted as  $\pm 3\%$  variation in the split ratio for S and P polarized light, leading to typical velocity errors of  $\pm 7\text{ms}^{-1}$ .

There are two approaches to the positioning of the illuminations frequencies relative to the iodine absorption line. In the first a signal and reference image are captured similar to conventional PDV. The first illumination frequency is tuned just off the low frequency side of an absorption line to lie in a 100% transmission region of the iodine transfer function (Fig. 1. point A). A reference image is then acquired. The second illumination frequency is positioned at approximately midway (50%) on the iodine cell transfer function (Fig. 1. point B), and a signal image is acquired. The two images can then be processed as in conventional PDV, by dividing the two images to produce a normalised transmission image that is then used to calculate the frequency, Doppler shift and finally the velocity.



**Fig. 1.**Relative positions of the laser frequency, and the shifted frequency on a typical absorption feature for 2v-PDV (A and B/C denote the position of the illumination frequencies and A' and B'/C' the Doppler shifted frequency)

The second approach increases the sensitivity of the system by tuning the two frequencies to the positions shown as B and C in Fig. 1. With one source tuned onto the falling slope and the other on the rising slope, a constant Doppler shift will result in the further attenuation of one image to a lower signal level and the rise in the signal level in the other image. Dividing the difference of the images by the sum, and taking into account any difference in the gradients will give a result that has approximately double the sensitivity of the current PDV methods.

In our previous work in 2v-PDV we have concentrated upon making time-averaged velocity measurements using an argon ion laser at 514nm and systems were demonstrated using both the

normal and increased sensitivity schemes described above - Charrett et al. (2004a), Charrett and Tatam (2006). However as the two images are acquired sequentially it is not possible to make measurements on rapidly varying flows using this system. In order to make this possible a pulsed two-frequency PDV system using Nd:YAG lasers at 532nm, and a CCD camera capable of capturing two closely spaced images (~300ns) to effectively freeze the motion of the seed particles will be described in the remainder of this paper.

### **3. Experimental arrangement**

A schematic of the experimental arrangement is shown in Fig. 2. A custom dual pulse laser (dual Continuum NY61 lasers) is used to generate the two pulses closely separated in time. Each cavity is independently seeded allowing the laser frequency to be tuned to the appropriate positions on the iodine absorption spectrum. The frequency-doubled outputs at 532nm of each laser are combined and delivered via a laser arm and formed into a laser sheet using cylindrical lenses. The measurement region is then imaged using 35mm SLR camera lenses coupled to imaging fiber bundles. The bundles in use at Cranfield have four arms (each consisting of 600x500 fibers) that are combined at the detector head end, Nobes et al. (2004). Three of the arms are used to image the flow while the fourth is used to monitor the frequency of each laser pulse.

The detector head used in this work, shown in Fig. 3, consisted of two 12-bit, cooled CCD cameras (LaVision FlowMaster 3s). The cameras used are capable of operating in a double frame mode where two frames are captured in quick succession 300ns apart. The first frame has an exposure time set by the duration of the camera trigger pulse and the second frame is exposed for the duration of the readout time. For the 2v-PDV technique only a single CCD camera is required for the flow measurement, in this work the second camera and the beam splitter were included to allow the frequency of each pulse to be monitored during the measurement. This was achieved by imaging a portion of the beam using the fourth arm of the imaging fibre bundles. The frequency of each laser pulse can then be determined by taking the ratio of the image intensities as in conventional PDV. The method has the disadvantage of reducing the signal levels falling on the signal CCD as approximately 50% of the light is diverted to the second camera.

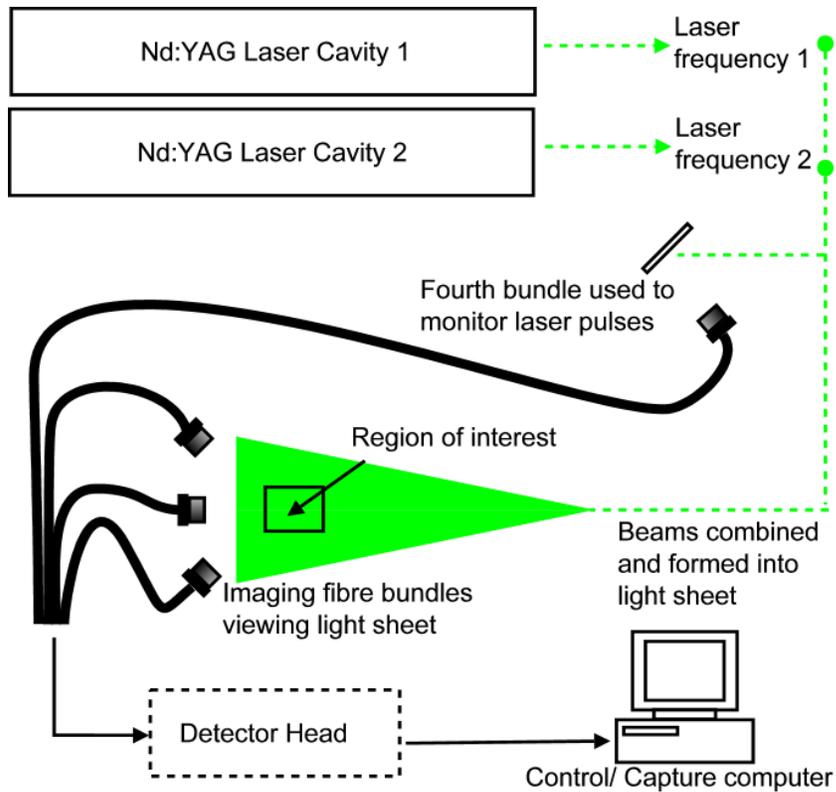


Fig. 2. Schematic showing the experimental arrangement.

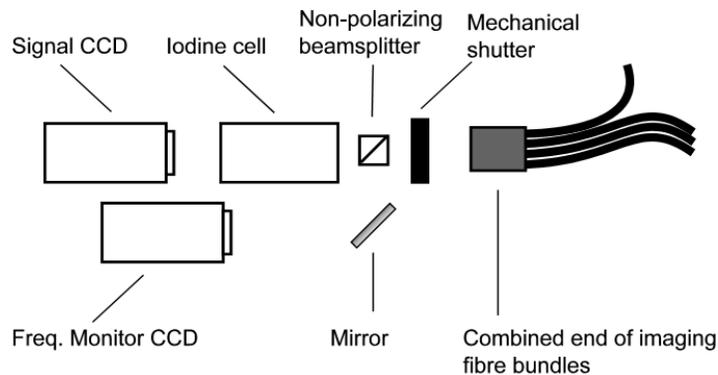
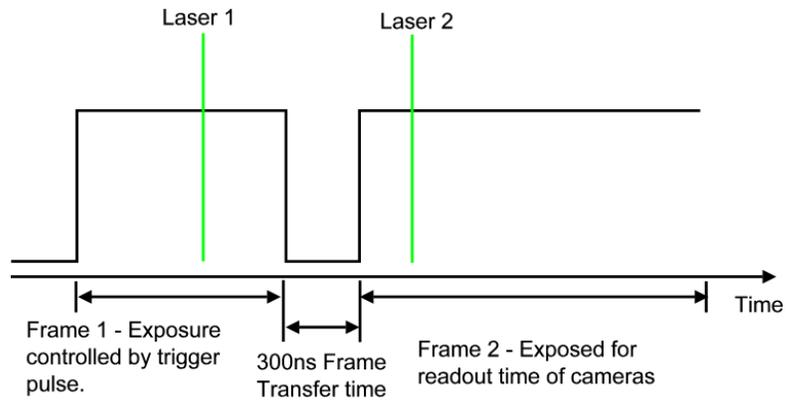


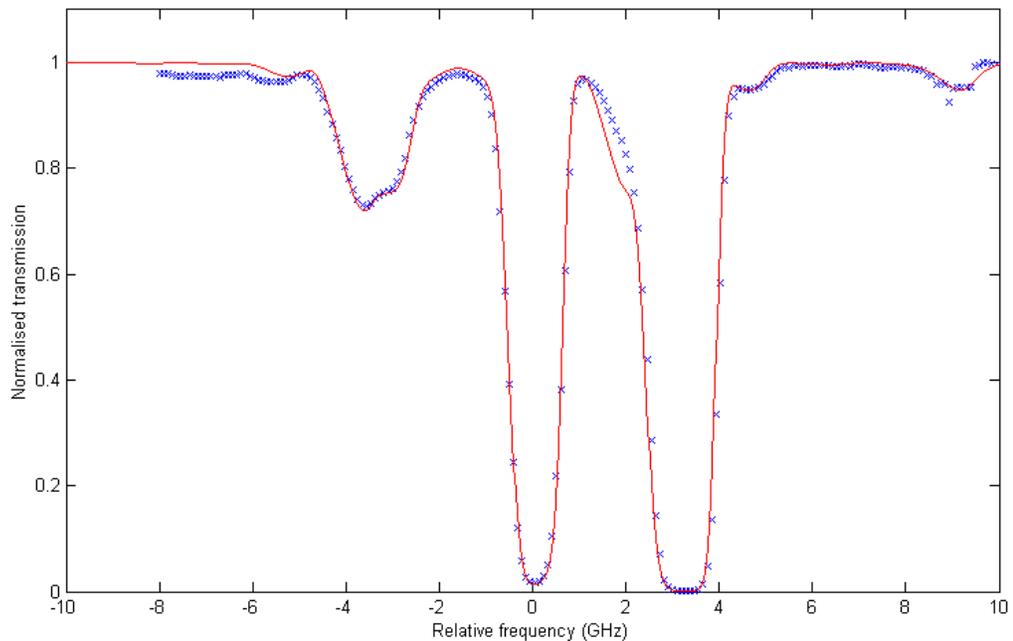
Fig. 3. Schematic of the detector head arrangement

The relative timings of the CCD exposures and the laser pulses are shown in Fig. 4. The laser Q-switch timing and camera triggers are set so that only a single laser pulse is recorded on each frame, laser one on frame one and laser two on frame two. Further pulses are prevented from being recorded by the use of fast mechanical shutter that is open for sufficient time to allow only a single pulse from each cavity to fall on the CCDs.



**Fig. 4. Timing diagram for CCD exposures and laser pulses.**

The iodine cell used is a 50mm long starved cell that is held at 50°C, 10°C above its starvation temperature of 40°C. This ensures that the iodine vapour pressure and hence absorption characteristics remain constant, Chan et al. (1995). The transmission spectrum of the cell was measured by tuning the Nd:YAG seed laser over its frequency range by varying the temperature of the seeded laser crystal oven. This is shown in Fig. 5 along with the predicted absorption for this cell calculated using the Forkey model - Forkey et al. (1997).



**Fig. 5. Scan of the iodine absorption line for the iodine cell used in this work (crosses) compared with the predicted absorption calculated using the model by Forkey et al. (1997) (solid curve)**

#### 4. Results and discussion

Preliminary measurements were attempted on the velocity field of a rotating disc and on a seeded air jet. The velocity field of a rotating disc provides a well-defined velocity field that can be used to characterise the performance of the system. The experiment was arranged with the light sheet illuminating the face of the disc and the three views positioned at the viewing angles shown in Table 1. The definitions of the viewing angles used are shown in Fig. 6. These angles were selected to provide a reasonable conversion, Reinath (1997), from the measured velocity components to the orthogonal velocity components that are aligned with the co-ordinate system.

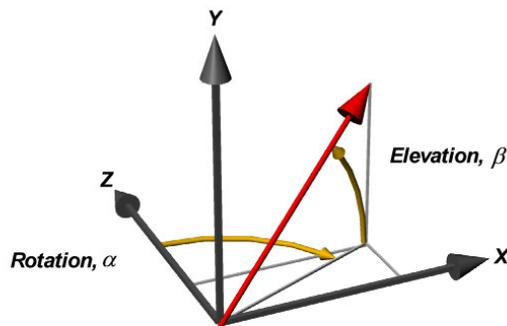


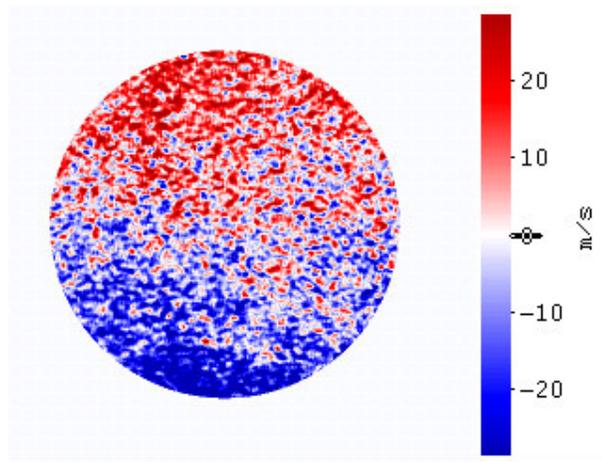
Fig. 6. Diagram showing the definition of the viewing angles; Rotation,  $\alpha$  (0-360°) and elevation,  $\beta$  ( $\pm 90^\circ$ )

Table 1. Definition of the viewing geometry used for measurements of the rotating disc.

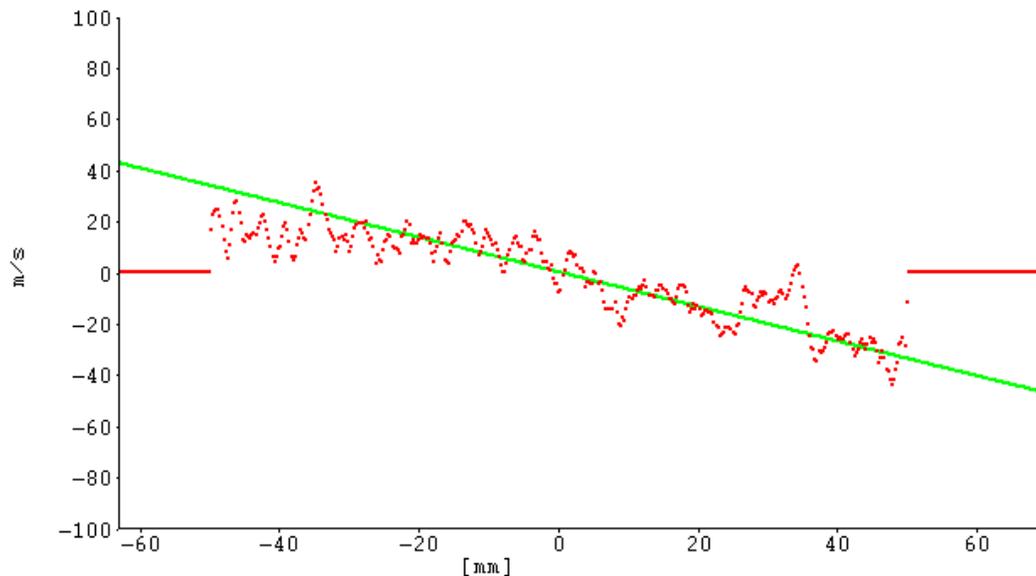
Angle ( $^\circ$ )	View 1	View 2	View 3
$\alpha$	135	180	225
$\beta$	0	45	0

The processed velocity components show the expected velocity trends and magnitudes, for example Fig. 7 shows a computed U (horizontal) velocity component, the velocity can be seen to vary from negative at the top of the disc to positive values at the bottom through zero in the center of the disc. Fig. 8 shows a profile taken through the center of this velocity component compared to a theoretical profile calculated from the disc's rotation frequency. However due to difficulties in evenly illuminating the face of the disc with the same intensity distribution for both laser pulses it was necessary to apply a correction similar to the 'white card' correction commonly used in PDV, Reinath (1997). This is generated by capturing images of the flow (or disc surface in this case) with both laser frequencies tuned to 100% transmission regions of the iodine absorption. Any Doppler shifts will now result in no change in the intensities and allows the differences in the illuminating sheets to be corrected for. The need for this correction was noted in our previous work [ref to RSI paper] where this correction was necessary when making measurements on a rotating disc but was

not needed when making measurements on a seeded airflow. This was because the poorly focused light sheet used when illuminating the disc exaggerates any differences between the two light sheets used.



**Fig. 7. Example of a preliminary measurement made on the velocity field of a rotating disc, showing the computed U (horizontal component)**



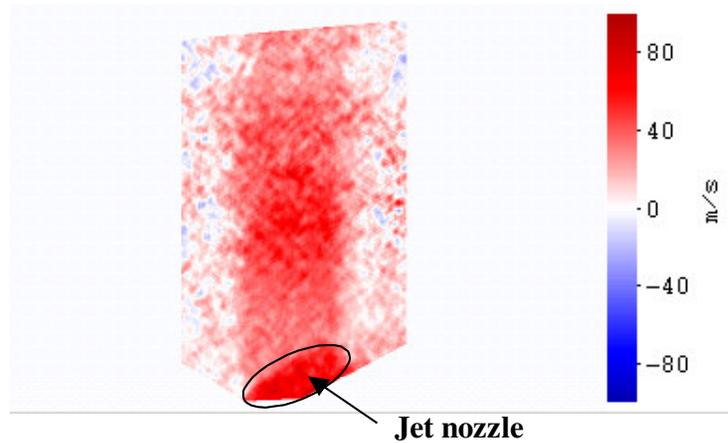
**Fig. 8. Profile taken through the center of the U (horizontal) velocity component image (red points) compared to the theoretical velocity component (green).**

A measurement was then made on a seeded airflow, an axis-symmetric air jet with a 20mm smooth contraction nozzle. This was seeded using a commercial smoke generator producing particles in the 0.2-0.3 $\mu$ m diameter range. Seeding was introduced to the air intake of the jet and to the air surrounding the nozzle. The views were positioned at the angles shown in Table 2. The light sheet was arranged in the positive x direction with the jets main velocity component in the positive y direction. Fig. 9 shows an example of a computed V (vertical) velocity component showing the main flow component of the jet. In View 2 the nozzle was visible (from scatted light) behind the

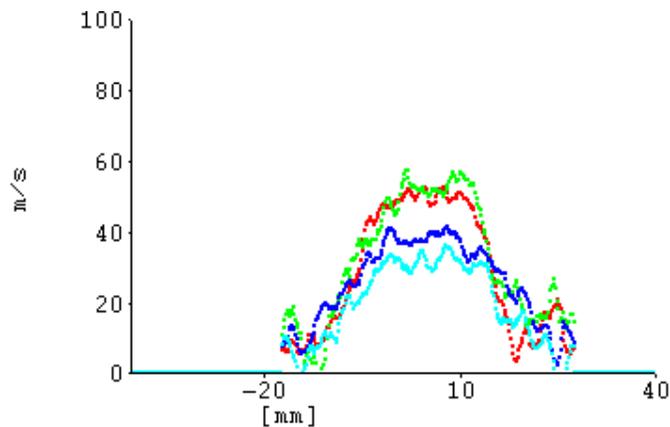
light sheet resulting in poor measurement in the region highlighted. As anticipated the ‘white card’ correction was no longer needed for this measurement. Fig. 10 shows profile taken across the velocity component shown in Fig. 9 at positions downstream from the nozzle, which shows the expected trends across the flow.

**Table 2. Definition of the viewing geometry used for measurements of the seeded air jet.**

Angle (°)	View 1	View 2	View 3
$\alpha$	135	45	45
$\beta$	0	45	-45



**Fig. 9. Example of a preliminary measurement made on the velocity field of an axis-symmetric air jet, showing the computed V (vertical) velocity component. Outlined in a region where the jet nozzle was visible in one of the images**



**Fig. 10. Horizontal profiles taken across the V velocity component shown in Fig. 9. Green ~20mm red ~35mm, blue ~50mm and turquoise ~65mm (from nozzle)**

## 5. Conclusions

A pulsed two-frequency PDV system has been constructed and demonstrated with preliminary measurements on both a rotating disc and a seed airflow. Although the expected trends in the velocity fields can be seen the measurements so far are very noisy and it is anticipated that further improvements in the alignment of the two laser beams will result in significant improvements.

Further improvements to the system could also be possible by improving on the method used to monitor the frequencies of each pulse. Currently the fourth imaging bundle arm is used to image a portion of each pulse and the beam splitter is used to send approximately 50% of the light to a reference camera. However this results in lower signal levels for the images of the flow. An alternative method of monitoring the laser frequencies could avoid this issue, for example using photodiode detectors.

Currently only measurements using the normal sensitivity scheme, with one frequency at 100% transmission and the other at ~50%, have been attempted. Using the increased sensitivity scheme described in section 2 and previously demonstrated using a CW time-averaged system - Charrett and Tatam (2006) - should further improve the measurements.

## 6. Acknowledgement

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

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