D.2.7. High Speed Imaging

Dr Adam Whybrew, Oxford Lasers, Oxon, UK Tel: +44 1235 554211

email: adam.whybrew@oxfordlasers.com

D.2.7.1 Properties of laser radiation which make it useful for high speed imaging

The first high speed movie was taken by William Henry Fox Talbot (1852). He showed that after photographing a rapidly rotating page of *The Times* newspaper illuminated by a short spark, the text was clear in the resulting negative. It was not obvious, when the laser was invented more than a century later (Maiman 1960), that this new technology might offer some new capabilities to the high-speed photographer. However, the fundamental properties of the laser which make it a useful tool for high-speed imaging were known then, and are discussed in this article.

Most high speed imaging is possible without lasers. For example, two of the most important industrial applications of high speed imaging – machine vision and car crash testing - rarely employ laser illumination. Fuller (1997) has reviewed conventional lighting techniques for high speed imaging, touching also on laser illumination. Fuller’s review is found in an excellent introduction to the technology, techniques and applications of high speed photography (Ray 1997) in a book which also includes a contribution from Errey (1997) on the use of laser illumination. There have also been a series of High Speed Photography Conferences in San Diego, USA, covering a variety of topics both with and without laser illumination (see, for example, Hogan 1990).

Short duration pulses

Lasers offer a fast but controllable way to extract energy rapidly from a storage medium. Pulse compression techniques, described in C.2.3, can be used to squeeze the duration of a single pulse of laser light to a few femtoseconds.

The short duration of the laser pulses can be used to illuminate and so “freeze” the motion of fast-moving objects in the camera image. The laser pulse duration required to freeze motion depends on the size of the object in question, and its velocity. If we assume a characteristic linear dimension, *d*, and a speed, *v*, then the laser pulse should have a duration, *t,* short enough for the object to move less than, 10% of its characteristic dimension during the pulse. The choice of 10% is arbitrary, but is sufficient blurring to degrade even qualitative measurements. In other words, we require that

$$t \leq \frac{d}{10v}$$

Therefore, the shortest pulses are required for the smallest and fastest objects. The smallest particles we can resolve optically are about 1 micron, and the fastest velocities available on Earth are about 10 km s^{-1}, suggesting we require minimum laser pulse durations of around 10 ps. This means that femtosecond lasers are never required for high speed imaging, but this is an extreme example, and for the overwhelming majority of applications, laser pulses in the 1 ns to 1000 ns range are sufficient.

It is very important to realise that when using pulsed lasers with high speed cameras, the duration of the flash from the laser determines the exposure time – the camera exposure time is not relevant. This is illustrated in Fig. D2.7.1, which shows images of the same spray, taken by the same camera at the same speed, illuminated in one case by continuous lighting (direct current halogen lamp), and in the other case by 25 ns pulses from a copper vapour laser. From these images it is clear that the laser-illuminated image is qualitatively better than the continuously-illuminated one – notably because the short pulse duration has frozen the motion, revealing the continuous-sheet region of the spray, as well as the break-up region and the individual droplets.

Low divergence

The low-divergence of lasers can be useful for high speed imaging if the lightsource must be situated far from the subject to be imaged (for example, when imaging explosions). However, it is usually a secondary property of the low-divergence nature that is most useful – namely that a laser beam can be bought to a very tight focus. This lends itself to two experimental configurations: fibre beam delivery and lightsheets.

Fibre-delivery

Delivery of laser light through optical fibres can be extremely useful in order to illuminate inaccessible subjects (Clowater *et al.* 1992). For example, Rao *et al.* (1992) used an optical fibre to deliver light in order to study combustion processes within a firing diesel engine cylinder. An illustration of their work is shown in Fig. D2.7.2.

Coupling light into optical fibres is a delicate process, and is described in more detail in C.4.3. The most common approach is to focus a beam onto the core of an optical fibre, after the beam has emerged from the laser cavity. There are conflicting considerations that influence the choice of fibre to be used, namely:

- The output of light from a well-scrambled multimode optical fibre is well-described as a planar source of size equal to the core section at the output end of the fibre, and emitting into an angle equal to the acceptance angle of the fibre. If this light must be refocused (for example to form a lightsheet), then the smallest focus that can be achieved is typically around one half of the core diameter. Therefore for a fine focus or a thin lightsheet, a narrow core is desirable.
- A laser focus is associated with a high fluence and peak intensity – indeed this can be exploited to drill hard materials (see D.1.6). However, for efficient coupling into the fibre, the focus must be no larger than the fibre core, and so to avoid damage to the fibre, a large core is desirable. This means that the smallest fibres that can be used with high power lasers have core diameters ranging from about 400 microns upwards, and 600-1000 microns is typical.

Lightsheets

A sheet of light can be formed from a laser by focusing the beam with astigmatic optics, such as cylindrical lenses (Raffel & Willert 2001). Lightsheets are used to illuminate complex flow structures, for example in sprays, and are essential for the particle image velocimetry (PIV) technique (See D.2.2). Sheet lighting is often the only way to simplify the structure of a turbulent flow sufficiently to gain insight into its behaviour. Generally, the thinner the lightsheet, the better. Figure D2.7.6 shows an example of lightsheet illumination – used to visualise the spray from a metered dose inhaler.

Laser speckle

Lasers are well known for emitting light into a very narrow range of wavelengths. This gives rise to two considerations in high-speed imaging – laser speckle and high-brightness imaging. Laser speckle (Dainty 1975) is usually undersirable, introducing an intrusive random background into the image intensity, although it can be exploited in the electronic speckle pattern interferometry (ESPI) technique (Meinlschmidt *et al.* 1996).

Speckle can be reduced by using fibre-optic light delivery (which scrambles the spatial coherence of the beam) and by using two or more spatially separated diffusers (Kashdan 2002). Speckle is exacerbated by narrow wavelength distribution, and the use of small apertures in imaging lenses. The use of small apertures in imaging lenses is often unavoidable but the wavelength distribution can be broadened (and speckle avoided) by judicious choice of laser (e.g. a diode laser, as used by Murphy *et al.* 2001, and compared with spatially-separated diffusers by Kashdan 2001), or by using the laser to illuminate a fluorescent material which re-emits over a broad spectrum, provided it does not lase (Oxford Lasers 2001).

High brightness imaging

It is often desirable to apply high speed imaging techniques to bright (incandescent) subjects. For example, type-approval of novel aircraft jet-engines requires a blade-off test in which one of the turbine blades is explosively fractured from a running engine. The manufacturer must demonstrate that no part of the engine escapes its outer protective canopy in the resulting explosion. The massive cost of such experiments means that the event is invariably surrounded by high-speed cameras in order to establish the cause of any failure. However, a ball of fire is produced and this dazzles the cameras. Although it is possible to use filters to prevent this, it then becomes impossible to see the event before the fireball, as there is insufficient light to expose the camera. Oxford Lasers and General Electric have shown (in work which cannot be published for reasons of commercial sensitivity) that laser illumination techniques to be described in this section can eliminate this problem. Indeed they can be essential in any imaging application in which both incandescent and dark objects must both be imaged.

Bright objects emit light over a range of wavelengths, dependent on the temperature of the objects and their chemical composition. Laser illumination, is over a much narrower range of wavelengths. This is illustrated in Fig. D2.7.3, which shows how the light from a laser lightsource might compare with the light from a bright object. If we illuminate the bright object with the laser and place a filter in front of the camera which only allows the laser light to pass, then we make the bright object much darker, but have little effect on the laser illumination. By using widely-available multilayer interference filters, having a passband of 1-2 nm, we can achieve a reduction in intensity of a factor of ~125, or 7 photographic stops, by using this spectral filtering technique.

Even more contrast between the laser illumination and the bright subject can be achieved by using temporal filtering in addition to spectral filtering. A camera exposure time of 100 μs may be used, which is the shortest time typically available on electronic cameras. On the other hand, a copper vapor laser, which offers 30 ns FWHM pulses may be used. Section D 2.7.3. discusses the range of lasers available for high speed imaging. For high-brightness applications the copper vapour laser is usually the most suitable because it offers the shortest possible pulses of any laser type at a rate suitable for use with high speed cameras (a few kHz) and with sufficient pulse energy to be useful (a few millijoules) illumination. If a very high speed opto-electronic shutter is placed in front of the camera, the exposure time of each frame can be reduced to 100 ns, with all of the laser pulse still captured, and without the need for very critical adjustment of the timing window (with great care, shorter times are possible). In this case the brightness of the bright subject has been reduced by a factor of 1000 (the ratio of the 100 μs camera exposure time to the 100 ns shutter time), or 10 photographic stops, with no reduction in the apparent brightness of the laser.

Krishnaswami *et al.* (1997) have described an experimental arrangement for such a system, based on a copper-vapour laser. A different illustration of the technique applied to a firework is shown in Figure D2.7.4. These techniques have been applied to a range of applications, including research into welding, metal sprays, explosives, high-current electro-mechanical devices, and destructive testing of aircraft jet engines already described.

D 2.7.2 High speed camera technology

The technology of electronic cameras is moving spectacularly fast at the time of writing. The reader may well find the camera-company web sites listed in the references are the best source of current information.

High speed film

The first high speed cameras all used photographic film as the recording medium. Film is comparatively expensive, and is tedious to use, typically taking anything from 15 minutes to an hour to develop, and with only limited opportunity to preview the experiment. Nevertheless it is still used widely, mainly because it offers much greater sustained data rates than even the fastest electronic cameras.

Film cameras for use with lasers fall into several categories, and the most common types are:

- **Conventional intermittent-action cine cameras**. These are based on the conventional movie-camera design, in which the film comes to a complete stop during the film exposure, which limits the maximum exposure speeds to 500 images per second. (Photosonics)
- **High speed cine cameras with rotating prisms.** These cameras use a rotating multi-faceted prism, synchronised with the film motion, to project a moving image onto the moving film. This means that there is no net relative movement of image and film. With short enough laser pulses, the prism is not actually needed, since the laser defines the exposure time. Frame rates are up to 10 000 frames per second in full format, and 20 000 frames per second at half-height. It takes about a second for the film to accelerate to full speed, typically leaving about 2 seconds of full-speed recording time. (Hadland, Photosonics, Photec, NAC)
- **Rotating drum cameras** In rotating drum cameras a length of 35 mm format film (typically 1 m), is laid around the inside perimeter of an evacuated drum. The drum is rotated at high speed (typically 300 revolutions per second) and the image from the lens projected onto the film. In streak cameras the image is stationary, and the film moves underneath it, so short laser pulses (e.g. from a copper vapour laser) prevent blurring. Full-frame recording rates of a little more than ten thousand frames per second are achieved, with faster frame rates possible

simply by means of a suitable aperture limiting the height of the image on the film, giving a typical maximum frame rate of around 50 000 frames per second. (Cordin)

- **Rotating mirror cameras** can give framing rates up to 25 000 000 frames per second, but lasers having enough pulse energy to be useful cannot keep pace with these rates. These cameras have been reviewed by Rendell and Honour (1997) and are made by Cordin.

Electronic cameras

Over the past 10 years or so, electronic cameras have started to dominate the high-speed imaging arena. This is due almost entirely to their ease of use, since their capabilities (especially the sensitivity and the information storage rate, which is the product of the recording speed and number of independent elements, or pixels, forming each image) generally do not yet match those of film cameras. Various technologies are in use, often in combination with each other. These are:

- Charge Coupled Device (CCD) sensors. In these devices incident light is converted to electrons which are stored in capacitors. The readout of one pixel at a time limits the total speed of the camera, but it can be improved by multiple readout taps (Bixby 1982).
- Complementary Metal Oxide Semiconductor (CMOS) technology uses phototransisitors, rather than a photocapacitors (Wong 1999). Compared with CCDs, CMOS devices generally offer lower sensitivity (because more of the area which would be available to light-sensitive components is needed for ancillary electronics), but higher speed for a given cost since the production processes used to make integrated circuits can be used to make CMOS sensors almost without modification.
- On-chip pixel storage. Many electronic sensors have multiple sets of pixels on the same chip. Generally only one set is light sensitive, and the others may have a physical barrier to the light reaching them. The image is shifted from the light-sensitive to the non-light sensitive pixels after each exposure, for all the pixels at the same time. This can be done very fast – typical times are in the 200 ns to 1 microsecond range. This is useful since it allows a technique known as frame-straddling. This involves firing a laser at the end of one camera exposure, and then the beginning of the next, so that the time between subject exposures is much less than

the framing time. Some cameras have many sets of pixels on chip such as the SMD cameras described by Howard *et al.* (1997), and these are used to allow a limited number of frames to be captured in quick succession. Etoh (2001) has reviewed the current state of the art.

- Image-splitting: Some cameras take the incoming image and split it using a beamsplitter onto two to eight independent sensors (Honour, 1994). Each camera requires a high-speed opto-electronic shutter, so that it is light sensitive only at the correct time. These shutters generally take the form of third generation image-intensifiers, using microchannel-plate (MCP) technology. These cameras provide the fastest possible frame rates (1 000 000 to 100 000 000 frames per second), but the two main disadvantages of this type of camera are cost (expensive components must be duplicated) and the limited number of frames that can be stored.

The table below lists (in order of increasing storage bandwidth) some high-speed cameras. Note that many cameras can be made to run faster (often ten times faster) by reducing the image resolution.

Camera type	Example (and non-exhaustive list of other suppliers of a similar specification)	Max. Resolution (pixels)	Speed at max resolution (frames per second)	Number of frames stored	Pixels per second (million)
High speed CCD	Roper Motionscope (also: NAC, Weinberger, Photron)	512 x 512	250	2 048	65
Low cost CMOS	Vosskuhler HCC 1000	1000 x 1000	462	512	462
State of the art (Oct 02) high speed CMOS	Vision Research Phantom 5 (also: NAC, Roper, Photron)	1024 x 1024	1 000	4 096	1 048
Near-launch high-speed CMOS (Oct 02)	Vision Research Phantom 7	800 x 600	6 000	8 400	2 880
Film, rotating drum, streak	Cordin 317	2400 x 1800	13 500	52	58 000
2-image PIV camera (uses on-chip storage)	PCO Sensicam (also: Roper, Hammamatsu)	1280 x 1024	5 000 000	2	6 600 000
Split image, multi-sensor (also use on-chip storage)	Cordin 220, (also: PCO, Hadland)	1300 x 1030	100 000 000	8	134 000 000

D.2.7.3 Choice of laser

A number of lasers are available for high speed imaging. Generally the user has a choice between pulse energy, pulse duration, repetition rate, and cost. Some commonly used lasers are shown in the table below.

Laser type	Example	Wavelength (nm)	Pulse length (ns)	Max. pulse repetition rate (Hz)	Pulse energy (mJ)
Copper vapour	Oxford Lasers LS 20-50	511+ 578	10-30	50 000	0.5-5
CW pumped Q-switched YAG	Lee Laser LDP-50-MQG	532	120-450	50 000	0.5-5
Flash-pumped Q-switched YAGs	New Wave Solo PIV, Quantel twins	532	10-20	5-50 & 20 000 000 (burst)	10-500
Argon Ion (CW), with chopper	Coherent Innova	488+ 514	Depends on how chopper/scanning is used. Laser power typically 5-10 W		
Diode laser	Oxford Lasers HSI 5000	808	500-100 000	5 000 & 400 000 (burst)	0.09- 17.5

From this we can see that the copper vapour laser (Hogan 1990) offers high repetition rates, short pulses, and moderate pulse energy. CW pumped Q-switched YAG lasers offer similar features, in a smaller package, but with pulse durations 5 to 10 times greater. Flash-pumped Q-switched YAG laser pairs comprise two lasers, from which the beams are combined. They are used almost exclusively for PIV since they can only provide two exposures in short succession.

Argon ion lasers give continuous output and this can be chopped into shorter duration bursts, or the beam can be scanned in order to generate a light sheet. Although in widespread use, their low power, very high electricity and cooling requirements, and short service interval, means that they are now generally being replaced by solid state (diode laser) alternatives, offering 20 times the power for short pulse applications, in a much smaller and easier to use package (Whybrew *et al.* 1999).

Illumination techniques

Various illumination techniques are used for high speed photography:

- Backlighting involves providing a bright screen behind a subject, which appears dark against it. It is particularly suitable for sprays, and is required for image based sizing (section D.2.8).
- Sheet lighting is used to slice through complicated three dimensional fluid flows, and is used for sprays and liquid flows. It is much the most common form of lighting employed for PIV (section D.2.2.2). Of the lighting techniques described here it is the only one that can only be well-performed with a laser rather than a conventional lightsource.
- Front lighting consists of illuminating the subject from the front and viewing light reflected or scattered by the subject. It is suitable for applications where there is optical access from one side only (e.g. for use with endoscopes) or for looking at the motion of machines or

manufacturing processes. Front lighting is the type of lighting used in most conventional photography, such as landscapes and portraits of people.

- Shadowgraphy and Schlieren photography visualise variations in fluid density or refractive index, e.g. shock waves behind projectiles, convection currents, combustion processes (Gillespie *et al.* 2000), explosive gas flows (Kendall *et al.* 1999). This makes these techniques fundamentally different from the others described because the contrast they produce could otherwise be invisible to the human eye. Shadowgraphy is simple to set up. Schlieren photography is more sensitive, since it measures the first derivative of the density, but is more difficult to set up. Practical and theoretical details are given by Fuller (1997b).

D.2.7.4 Application examples

Time-resolved PIV in engines

Airflows in automotive engines are vital to the performance of the engine – affecting fuel mixing, combustion and exhaust. Almost all car companies use laser based imaging in order to visualise and measure these flows.

For example, engineers at the Rover company (Reeves *et al.* 1999, Whybrew *et al.* 1999) have performed time-resolved PIV on airflows within a petrol engine combustion cylinder. Their experiments illustrate many of the compromises involved in high-speed imaging applications. These were

1. Choice of camera: They chose to use the fastest electronic camera (capable of taking at least 360 images) available at the time, the Kodak 4540. A high speed film camera, would have offered a recording bandwidth almost 200 times greater, but the extra time required to use film would have severely reduced the usefulness of the result.
2. Choice of laser: The aim of the experiment was to take images with a separation in crank angle of one degree, but at useful engine running speeds (1500 rpm). This meant that a frame rate of 9 000 frames per second was required. This restricts the choice of lasers to a copper vapour laser or a cw-pumped q-switched Nd:YAG laser, but in either case, only a few millijoules of energy per pulse was available (rather than the tens of millijoules more often used in PIV experiments – for more information see the discussion in section D.2.2.2.)

3. Seeding: In order to achieve sufficient scattering from these relatively low pulse energies, large (40 micron) seeding particles were required to visualise the flow. However, these were incapable of following detailed turbulent flow structures. But, the low resolution of the camera (256 x 128) at this speed also meant that the detailed turbulent flow structures could not be resolved anyway.

These choices meant that it was the time-resolved behaviour of the bulk flows which was measured, rather than the instantaneous detailed structure. Reeves *et al.* (1999) reported that even in the large scale flows, complicated spatial and temporal structure was found, and this type of measurement was required to understand the effect of swirl within the cylinder.

Agricultural spray characterisation

The properties of pesticide sprays in agriculture are essential to the performance of the spraying system. Drop size is a crucial parameter, having a particular influence on the undesirable wind-drift of the pesticide. The British Crop Protection Council (BCPC) have defined a set of standard spray nozzles, against which the drop-size distributions of other nozzles can be compared (Southcombe *et al.* 1997). Herbst (2001) and Murphy *et al.* (2001) have reported drop size distributions using a sizing technique based on the analysis of images taken with a high-magnification high speed imaging system. This technique is described further in section (D.2.8). However, Murphy *et al.* (2001) have also reported how high speed imaging could also be used to visualise very different spray breakup regimes obtained from various nozzle types, giving an understanding of how the different drop size distributions were produced. Some images are reproduced in Fig. D2.7.5.

Drug delivery sprays

Drug delivery direct to the lungs is a well established tool for the treatment of asthma. The metered dose inhaler (MDI) is a widely used device for this (Purewal and Grant 1998). In order to achieve efficient delivery to the lungs, drop sizes in the spray cloud must be tightly controlled. Drops smaller than about 1 micron tend to be exhaled, while drops larger than 5 microns tend to stick to the throat rather than reaching the lungs (Purewal 1998). Also important are the duration, velocity and degree of turbulence of the spray, which affect both throat deposition and patient comfort. In order to check for manufacturing defects, and equivalence between innovative and generic devices, it is also necessary to make measurements of the spray pattern and spray plume angle (United States Food and Drug Administration, 1998). Measurements of all of these properties (drop size, velocity, duration, turbulence, spray pattern and plume angle) can all be made using laser-based high speed imaging techniques, largely with the same equipment. Figure D2.7.6 gives an example of a high resolution image of an MDI spray, iluminated with a laser lightsheet.

- Spray duration can measured simply by noting the time of appearance and disappearance of the spray in a high-speed movie (Brambilla *et al.* 2001).
- Cone angle (longitudinal) and spray pattern (cross sectional) can be measured by illumination with a laser lightsheet and combination of the frames from a high speed movie. Software measurement of the resulting images can yield the cone angle and the spray pattern.
- Drop size distribution can be measured using the image-based particle/droplet image analysis (PDIA) sizing technique described in section D.2.8.
- For slower sprays (e.g. MDI plumes in spacers which are used to reduce flow velocity and enhance patient comfort) time-resolved PIV at up to 10 000 frames per second is now possible, using the latest generation of CMOS cameras. For faster sprays, more conventional non-time resolved PIV is required to measure the detailed flow structure , but the bulk flows can be measured with a frame rate of only a few thousand frames per second (Brambilla *et al.* 2001).

Summary

The application of lasers to high speed imaging applications adds extra capabilities to high speed cameras, whether electronic or digital. Laser, camera, lighting technique and image analysis tools must all be chosen to complement eachother and with the application in mind. Notably, lasers can be used to eliminate motion blur, light inaccessible regions, slice through complex three-dimensional flow structures, see through explosions, arcs, and flames, and make quantitative measurements of velocity, and particle/droplet size, temporal and spatial distributions.

References

Bixby, J A 1982 *Fast frame rate sensor readout* US Patent 4,322,752

Brambilla, G, Davies, R J, Ferraris, A, Ganderton, D, Keay, F, Lewis, D A, Meakin, B J, Murphy, S D, Nicholls, T R. *Plume profiling of Beclomethasone Diproprionate pMDIs.* 2001. American Association of Pharmaceutical Sciences (AAPS) Annual Conference, 2001.

Clowater L, Hamady F, Schock H, 1992. *Fiber Optic Imaging System for Remote Location Flow Vizualization Studies.* SAE Technical Paper Series 920305, Intl. Congress & Expo; Detroit, MI, USA, Feb 24-28 1992.

Cordin: www.cordin.com

Dainty, J C (Editor) 1975 *Laser Speckle and Related Phenomena* Springer Verlag Topics in Applied Physics **9** (Berlin, Heidelberg and New York: Springer Verlag Publishing)

Errey, K H E Pulsed lasers in high speed imaging *High Speed Photography and Photonics*, ed S F Ray (Oxford: Focal Press) pp 150-163

Fuller, P W W, 1997a Lighting for cine and high speed photography *High Speed Photography and Photonics*, ed S F Ray (Oxford: Focal Press) pp 29-47

Fuller, P W W, 1997b Flow Visualization *High Speed Photography and Photonics*, ed S F Ray (Oxford: Focal Press) pp 254-280

Gillespie L, Lawes M, Sheppard C G W, Wolley R, 2000. *Aspects of Laminar and Turbulent Burning Velocity Relevant to SI Engines.* Advances in Combustion, SP-1492, SAE Technical Paper Series 2000-01-0192, SAE 2000 World Congress, Detroit, Michigan, USA March 6-9 2000.

Hadland: www.hadland1.demon.co.uk

Herbst A *Droplet sizing on agricultural sprays – a comparison of measuring systems using a standard droplet size classifiction scheme*. 2001 ILASS Europe, Zurich 2-6 September 2001

Hogan D C, Applications of copper vapor laser lighting to high speed motion analysis. *Proc. SPIE,* **1346**, pp324-330

Honour J, 1994 A new high speed electronic multi framing camera. *Proc SPIE* **1801** pp643-648

Howard, N E, Gardner D W, Snyder D R 1997 Million frame per second CCD camera with 16 frames of storage, with 16 frames of storage in Ultrahigh and High Speed phography and Image based motion measurement, *Proc. SPIE,* **3173**, p40-47

Kashdan, J T 2002 *Experiments on Intermittent Swirl-Generated Sprays*, PhD Thesis, Imperial College, London.

Kendall, M A F, Quinlan, N J, Thorpe, S J, Ainsworth, R W, Bellhouse, B J, 1999 Particle dyanmics of a high-speed needle-free drug delivery system. *Paper 3320 22nd Intl. Symp. on Shock Waves*, Imperial College, London

Krishnaswami K, Tilleman M M, Choi S S, Krivoshlykov S G, 1997. *High Speed Photographic System for Objectives with Highly Radiant Backgrounds*. SPIE **3108**, pp50-57.

Maiman, T H 1960 Stimulated optical radiation in ruby masers. *Nature* **187,** 493

Meinlschmidt P, Hinsch K D, Sirohi R S (Editors), 1996. *Electronic Speckle Pattern Interferometry: Principles and Practice.* Society of Photo-Optical Instrumentation Engineers (SPIE) 1996, USA.

Murphy, S D, Nicholls, T, Whybrew, A, Tuck C R, Parkin C S, 2001 *Classification and imaging of agricultural sprays using a particle/droplet image analyser* British Crop Protection Council Conference 2001 (BCPC 2001 Weeds), Brighton, UK

NAC: www.nacinc.com

Oxford Lasers, 2001, *Fluorescent Diffuser* GB Patent application GB0117989.4

PCO (Precision Computer Optics): www.pco.de

Photec: www.photo-sonics.co.uk

Photosonics: www.photo-sonics.co.uk

Photron: www.photron.com

Purewal, T S 1998 Formulation of Metered Dose Inhalers *Metered Dose Inhaler Technology* eds Purewal and Grant, Interpharm Press, Buffalo Grove, IL, USA pp9-68

Purewal, T S, Grant, D J W (Editors) 1998. Metered Dose Inhaler Technology eds Purewal and Grant, Interpharm Press, Buffalo Grove, IL, USA pp9-68

Raffel M, Willert C E, 2001. *Particle Image Velocimetry* (Berlin & Heidelberg: Springer-Verlag)

Rao, K K, Winterbone, D E, Clough E, 1992 Laser Illuminated Photographic Studies of the Spray and Combustion Phenomena in a Small High Speed DI Diesel Engine. *SAE Technical Paper Series, Intl. Fuel and Lubricants Meeting and Exposition, San Francisco, 1992, Paper 922203*

Ray, S F, 1997 *High Speed Photography and Photonics*, (Oxford: Focal Press)

Reeves, M, Towers, D T, Tavender, B, Buckberry, C H 1999 A high speed all-digital technique for cycle-resolved 2-D flow measurement and flow visualisation within SI engine cylinders. *Optics and Lasers in Engineering* **31**, 4, pp247-261

Rendell, J, Honour, J. High speed cine systems. *High Speed Photography and Photonics*, ed S F Ray

(Oxford: Focal Press) pp 68-80

Roper Scientific: www.roperscientific.com

SMD (Silicon Mountain Design): www.dalsa.com

Southcombe, E S E, Miller, P C H, Ganzelmeier, H, van de Zande, J C, Miralles, A, Hewitt, A J, 1997. *The international (BCPC) Spray Classification System including a drift potential factor*. The 1997 Brighton Crop Protection Conference – Weeds, Brighton, UK, November 1997, pp371-380

Talbot, W H F 1852 *On the production of Instantaneous photographic images* Phil. Mag. (4th series) 73-77

United States Food and Drug Administration 1998: *Metered Dose Inhaler (MDI) and Dry Powder Inhaler (DPI) Drug Products Chemistry, Manufacturing, and Controls Documentation*: Draft Guidance for Industry. US FDA, 5600 Fishers Lane, Rockville, MD 20857, USA.

Vosskuhler: www.vdsvossk.de

Weinberger: www.weinberger.ch

Whybrew A, Nicholls, T R, Boaler, J J, Booth, H J 1999 *Diode lasers - a cost effective tool for simultaneous visualisation, sizing, and velocity measurements of sprays*. ILASS Europe 1999, Toulouse, France

Whybrew,A, Reeves, M, Slagle, R L, Boaler, J J, Baughan, A K, Nicholls, T R, Towers, D P, Tavender, B, Buckberry, C H. 1999. *Two techniques for all-digital time-resolved PIV*. PIV 1999, Santa Barbara, CA, USA.

Wong H-S 1999. *Overview of CMOS Image Sensors*. NTSC/PAL VHS video published by Society of Photo-Optical Instrumentation Engineers (SPIE), USA. ISBN: 0-8194-3381-0

Further reading

Ray, S F, 1997 *High Speed Photography and Photonics*, (Oxford: Focal Press) Covers much of the material in this article in greater depth, although lacks the latest developments in electronic camera technology. At the time of writing it is out of print, but the Association of High Speed Photography and Photonics (www.ahspp.com) may have more information about this.

Figures

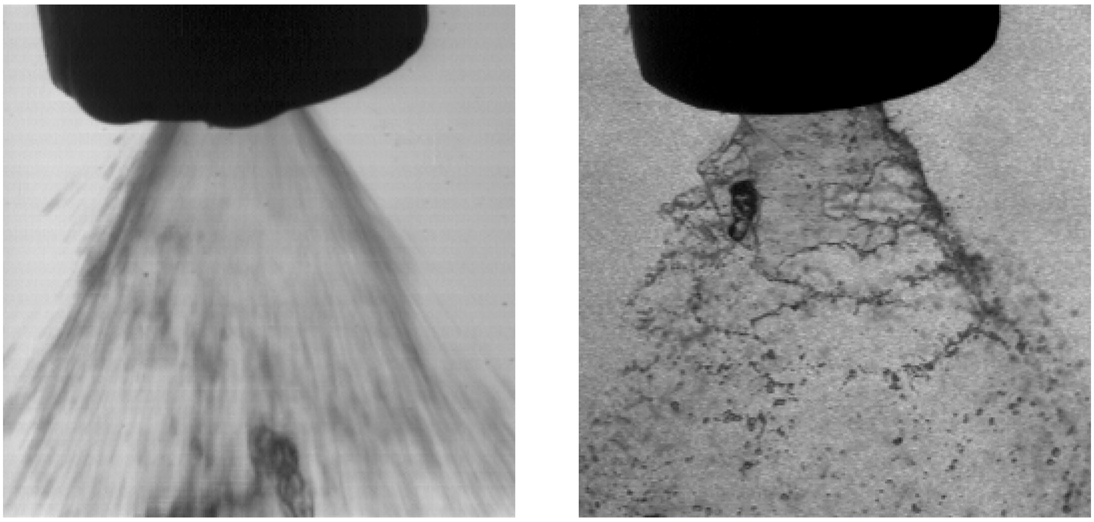

Figure D2.7.1: Effect of laser illumination to freeze motion. Both images are of an agricultural sprayer, taken at 4500 frames / second. In the image on the left continuous illumination is used, while for the image on the right, 25 ns pulses from a copper vapour laser have been used to freeze the motion. Courtesy Oxford Lasers.

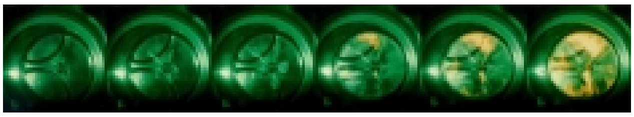

Figure D2.7.2. A sequence of stills from a high speed movie of diesel fuel injection. Taken with a film camera and copper vapour laser illumination. Courtesy K.K. Rao.

Figure 3

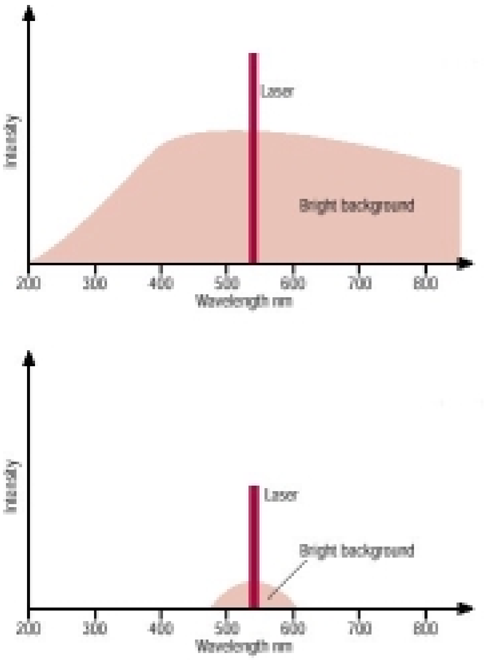

Figure D2.7.3: Wavelength spectrum emitted by a bright object, and by a laser, under normal conditions (upper) and as viewed through a narrowband interference filter (lower). Courtesy Oxford Lasers.

Figure D2.7.4: Both images show a burning firework, used to demonstrate the high-brightness imaging technique. On the left under normal illumination – the hot region is over-exposed, and the cold region is under-exposed. On the right, the high-brightness imaging technique is employed, and both regions can be seen clearly. Courtesy Oxford Lasers.

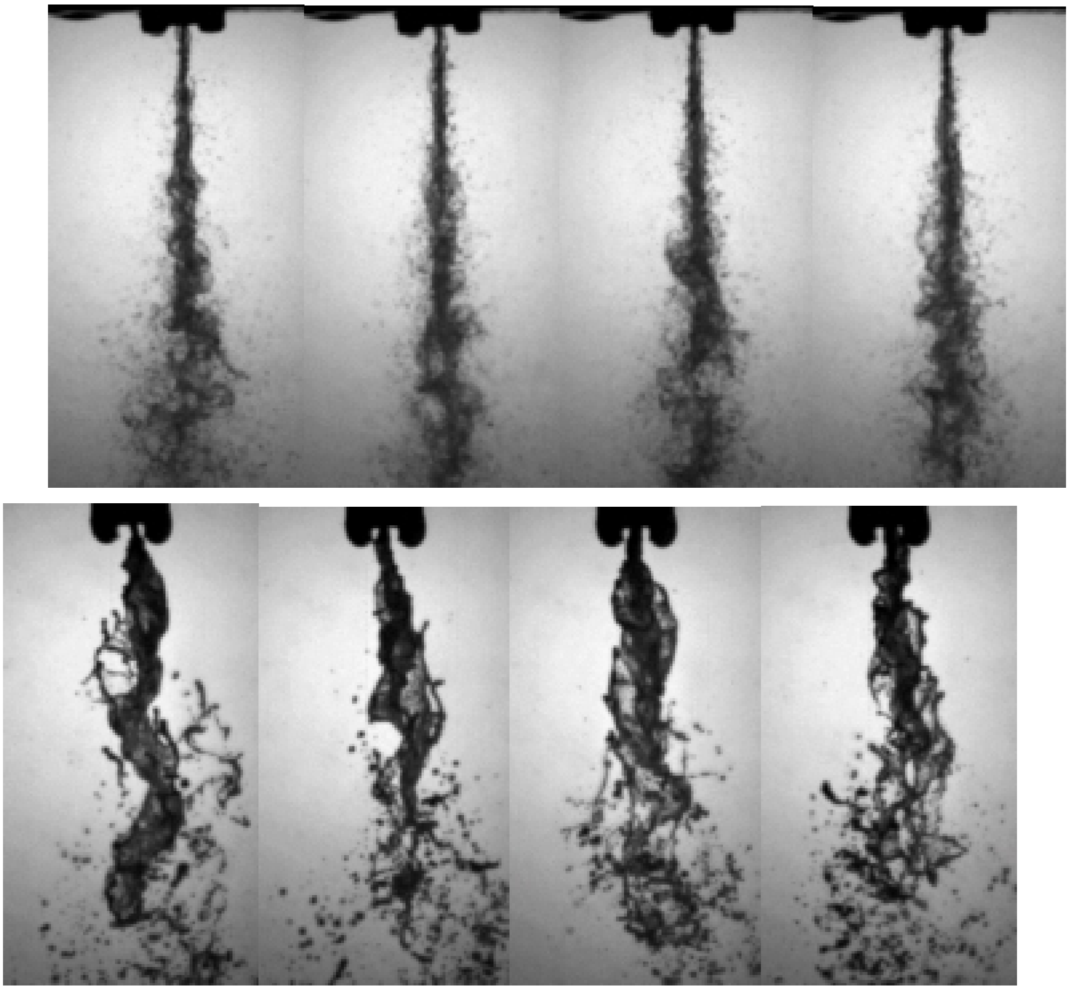

Figure D2.7.5 Sequences of images from a high speed movies showing the different spray break-up properties of agricultural sprays depending on the nozzle type used. (Murphy *et al. 2001*).

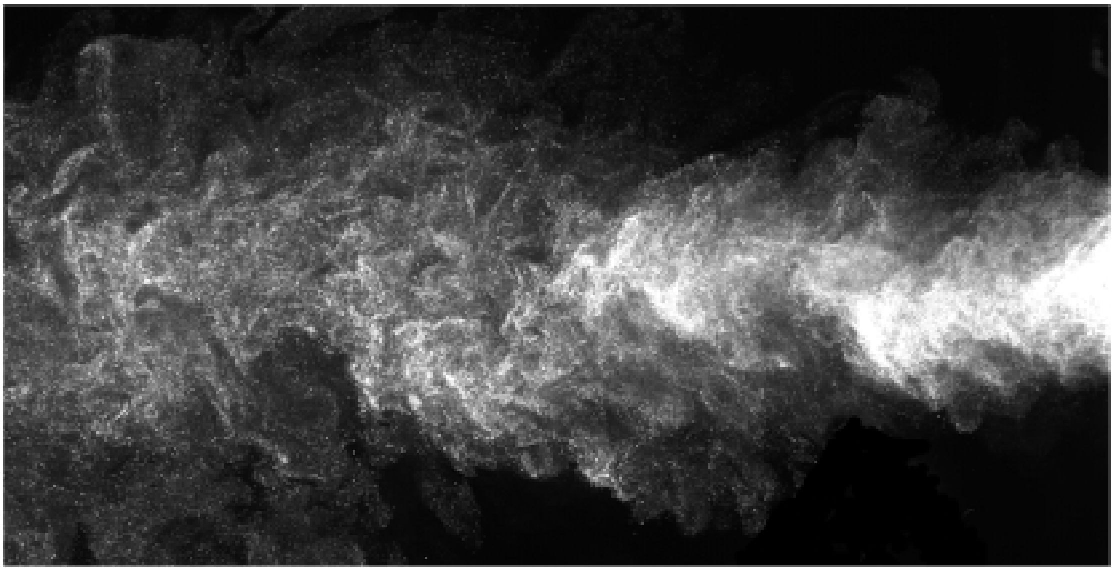

Figure D2.7.6. Spray plume from a metered dose inhaler, illuminated with a laser lighthseet. Courtesy Oxford Lasers.