Methodology for investigation of diffuse reflections in tunable diode laser absorption spectroscopy

D Masiyano, J Hodgkinson and R P Tatam
Engineering Photonics Group, Cranfield University, MK43 0AL, Bedfordshire, UK
E-mail: r.p.tatam@cranfield.ac.uk

Abstract. We present a methodology for investigating the deliberate use of optical scattering in tunable diode laser absorption spectroscopy. Diffusely reflecting materials have been investigated as a means of eliminating interference fringes. Their use introduces laser speckle that can contribute a random, rather than periodic, uncertainty to gas measurements. We have established a method for quantifying the uncertainty due to speckle and investigated ways of reducing it. Our analysis is based on a wavelength modulation spectroscopy model at 823 nm allowing the use of low cost CCD cameras for characterisation. Preliminary results confirm the viability of this approach.

1. Introduction
Tunable diode laser absorption spectroscopy (TDLAS) has great potential in trace gas detection, with applications in health, safety and environmental monitoring. The attractiveness of TDLAS includes high sensitivity, specificity and high detection speed. However, most TDLAS systems are limited in sensitivity by optical interference fringes superimposed on the measured spectrum\cite{1}. These result from unwanted etalons in the optical system. The fringes appear as periodic spectral features with sufficient amplitude to obscure weak absorption signals\cite{1}.

Design techniques to reduce etalon formation include the use of optical isolators, angling and antireflection coating of reflective surfaces. Techniques for eliminating or reducing the amplitude of the fringe signal include: asynchronous longitudinal dithering of optical elements, dithered Brewster angle plates, introduction of an asynchronous current in addition to the usual modulation current through the laser diode, and electronic low pass filtering\cite{2}\cite{3}. In many cases alignment of the optical components is critical. This often leads to complex designs with tight tolerances on optical component alignment, and can therefore be difficult and expensive to maintain in field instruments.

Here, we present an alternative approach based on the use of diffuse reflections, known in some circumstances to reduce interference fringes\cite{4}. This could lead to several benefits: (a) reduced complexity and costs in instrument manufacture, and (b) making systems less susceptible to misalignment, thereby increasing field robustness. However, their use introduces laser speckle that can contribute a random, rather than periodic, uncertainty to gas detection measurements. This research aims to investigate the conditions under which speckle reduces interference fringes. However, as laser speckle also contributes intensity noise, another important aspect of the project is quantifying and reducing the intensity noise due to speckle. We present preliminary results of a systematic study of these effects.
Our analysis draws heavily from the field of speckle and electronic speckle interferometry; therefore we begin with a brief introduction to speckle fundamentals. Ennos[5] and Jones and Wykes[6] have given a more comprehensive statistical analysis of speckle.

2. Theory

Light incident on an optically rough surface is scattered in random directions dictated by the topography of the surface. When the illumination is coherent and monochromatic, such as that emitted by a laser, the reflected components interfere and the surrounding region is filled with an interference pattern or laser speckle (also referred to as objective speckle). A speckle field can be seen in figure 1. A speckle field formed by collecting the scattered radiation field with a lens and focusing it on to the screen AB (figure 1) is termed a subjective pattern[5].

![Figure 1. Illustration of the formation of subjective speckle](image)

The lateral size of the individual speckles, \( \sigma_s \), at the screen AB is related to the effective f-number \( F# \), ratio of the focal length to aperture) and to the magnification \( M \) at which the lens is operating[5].

\[
\sigma_s = 2.44 \lambda \left( 1 + M \right) F#
\]  

(1)

The level of speckle intensity noise on a detector of size \( d \times d \) is related to the number of speckles \( N \) and therefore the speckle size.

\[
N = \frac{d^2}{\sigma_s^2}
\]  

(2)

We expect the level of speckle-related intensity noise for a single speckle field to be given by

\[
\frac{\Delta I}{I} = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{\sigma_s}{d}
\]  

(3)

or in terms of \( F# \) (using equation (1))

\[
\frac{\Delta I}{I} = \frac{2.44 \lambda \left( 1 + M \right) F#}{d}
\]  

(4)

3. Tunable diode laser absorption spectroscopy

The basic principle of TDLAS, its applications and comparisons of the different TDLAS techniques have been described elsewhere in the literature[1]. For our investigations, we have chosen to employ wavelength modulation spectroscopy (WMS).

3.1. Wavelength modulation spectroscopy

In WMS, the laser wavelength is modulated by varying the laser drive current at a frequency of several kilohertz. The laser wavelength can be simultaneously slowly scanned across a single gas absorption line by a large amplitude, low frequency ramp signal. The detected signal is then demodulated by a phase sensitive detector at the modulating frequency or its harmonics. The use of phase sensitive detection leads to a significant improvement in signal to noise ratio. Detection at higher harmonics shifts the operation to higher frequencies, at which laser excess noise is reduced.
4. Use of diffuse reflections in TDLAS

The formation of interference fringes and the principle of the proposed approach are illustrated in figure 2 below. Light from a laser diode was coupled into a singlemode fibre. One arm of a 50:50 coupler was directed onto a detector after passing through a gas cell. As shown in figure 2(a), multiple reflections could lead to formation of interference fringes. Figure 2(b) shows an equivalent system using diffuse reflections within the gas cell, plus apparatus used to diagnose the resulting speckle field. One arm of the coupler was directed to a gas cell model via a beam splitter. Light reflected from the diffuse surface end and the front window of the gas cell was imaged by the lens onto a CCD chip via a beam splitter and displayed on a monitor. The image on the monitor comprised a random interference or laser speckle pattern. If the CCD camera were to be replaced by a detector, the detector would measure the gas absorption signal plus random noise rather than systematic uncertainty (interference fringes).

(a) Basic TDLAS setup employing a 1650nm DFB laser

(b) Experimental model at 823nm

Figure 2 (a) Demonstration of the formation of fringes in a basic WMS set up (b) experimental setup for investigating the use of diffuse reflections in WMS. Key: DFB; distributed feed back, SM; single mode, PSD; phase sensitive detection
5. Experimental investigation

The experimental configuration shown in figure 2 (b) included: (i) a tunable diode laser driven so as to simulate a TDLAS based gas detection, (ii) a simulated gas cell containing a diffusely scattering surface in combination with one of a number of different types of window (a wedged window is illustrated), (iii) an interrogation system employing a silicon CCD camera. The setup at 823nm was a model of the longer wavelength (1651nm) gas detection and used a standard geometry for speckle interferometry experiments.

A 150mW single longitudinal mode laser diode (Spectra Diode Labs 5400 series) emitting at 823nm was coupled into a singlemode fibre with angle cleaved end faces via a Faraday isolator, thus preventing feedback into the laser cavity which could have detrimental effects on the optical characteristics of the diode. The laser operating current and temperature were controlled by Profile LDC 202 and TED 200 controllers respectively. The light was divided by a 50:50 coupler. One arm was passed to a Fabry Perot scanning interferometer (Tec-Optics FPI25) for monitoring the laser diode emission. The other arm was directed to the gas cell model via a beam splitter. A proportion of the light was specularly reflected by a window in the modelled gas cell. This will be referred to as the reference beam. The reference beam intensity was controlled by using an appropriate antireflection coating on the window. Light reflected from the diffuse surface end (a gas turbine compressor blade which was coated with retroreflective tape) of the gas cell will be referred to as the object beam.

The window on modelled gas cell could be aligned such that the object and the reference beams combined interferometrically to form a speckle interferogram (interferometric speckle) or misaligned such that only the object beam (non-interferometric speckle) was imaged by the lens onto the CCD camera (PearPoint P176). A calibrated variable aperture was used at the imaging lens to control the $F\#$ of the system. This is important because it determines the size of the speckles at the detector array (see equation (1)). The video signal from the camera was transferred to a frame grabbing card (National Instruments IMAQ PCI 1408) housed in a computer. The image was displayed on the monitor after processing in the Labview software environment.

According to equation (4), a reduction in intensity noise with increasing $F\#$ is expected. We have investigated the effect of speckle size on the intensity noise by conducting a series of experiments where the intensity noise was quantified for different effective $F\#$s of the collecting lens. We confirmed that the level of the background noise (for example, camera noise) was constant over the duration of the experiment and lower than the speckle related intensity noise. This was done by characterising the camera under dark conditions and illumination with a broadband light source. For experiments involving interferometric speckle, we confirmed that the object and reference beams were combining interferometrically by obtaining correlation fringes using electronic speckle pattern interferometry[5].

5.1. Experimental confirmation of speckle behaviour

We conducted experiments to verify that our configuration was valid for conducting speckle related investigations.

5.1.1. Speckle size. By varying the diameter of the adjustable aperture in figure 2(b) and observing the speckle field formed by collecting the scattered radiation with the wedged window removed, we confirmed that the lateral speckle size of the subjective speckle was related to the $F\#$ according to equation (4). Speckle fields corresponding to aperture diameters of 1mm and 0.6mm are shown in figure 3 below.

5.1.2. Interferometric speckle. To confirm that we could obtain interferometric speckle with our configuration, we performed a technique commonly referred to as static frame subtraction in Electronic Speckle Pattern Interferometry (ESPI)[7]. In subtraction ESPI, correlation fringes can only be obtained in the case of interferometric speckle.
In subtraction ESPI the speckle image from an object in its initial state is recorded and stored electronically. The object is then displaced and the digitized live camera signal of the deformed state of the object is subtracted pixel by pixel from the stored signal. Areas of the two images where the speckle pattern remains in phase will give a resultant signal of zero, while out of phase areas will give non-zero signals \[^6\]. Correlation ESPI fringes obtained with the experimental set up shown in figure 2(b) are shown in figure 3(c). These were obtained by heating the diffuse surface and then performing static frame subtraction as the diffuse object cooled down.

![Figure 3.](image)

5.2. Effect of wavelength modulation on speckle.
We investigated the level of uncertainty that relates to wavelength modulation by considering an intensity measurement made at one wavelength \(\lambda\) with a second measurement made within a short modulation period, at a second wavelength \((\lambda+\delta\lambda)\). We examined the effect of the wavelength modulation on interferometric and non-interferometric speckle on a scale relevant to gas detection using wavelength modulation spectroscopy.

5.2.1. Effect of wavelength modulation on non-interferometric speckle. For non-interferometric speckle, the expected change in the speckle field due to wavelength change is very small. For example, for \(F\# = 4\) and \(\lambda = 1650\) nm in equation (4), the proportional change in speckle size is \(2\times10^{-5}\) if the wavelength is changed by 4GHz. Therefore if we perform static frame subtraction as we vary the wavelength by current tuning the laser diode, we expect to observe a black field (corresponding to no change in the speckle field). We confirmed this experimentally by performing static frame subtraction whilst the laser wavelength was slowly scanned by 13GHz using a saw tooth signal. The average intensity of the resultant speckle field was recorded simultaneously. The procedure was repeated with no modulation applied to the laser diode (i.e. no wavelength change). The difference in the proportional standard deviations of the resultant average intensity for the two cases was found to be negligible and could be attributed to the laser intensity modulation associated with injection current modulation of laser diodes.

5.2.2. Effect of wavelength modulation on interferometric speckle. Interferograms obtained at different wavelengths have a phase difference that is associated with the wavelength change. Sirohi\[^7\] has shown that the phase difference \(\delta\phi\) created between such interferograms is equal to

\[
\delta\phi = 2\pi L\delta\lambda / \lambda^2
\]

The value of \(\delta\phi\) determines whether the observed speckle fields are in phase or out of phase, with the correlation coefficient being given by\[^7\]

\[
\rho(\delta\phi) = (1 + \cos \delta\phi) / 2
\]

Thus, for increasing \(\delta\phi\), the speckle fields alternate between \(\rho(\delta\phi) = 1\) (in phase) and \(\rho(\delta\phi) = 0\) (out of phase). If the speckle fields are in phase, we expect the speckle-related noise to reduce to zero for
differential measurements. If the induced phase change takes the value $\delta \phi = \pi$ the speckle fields are out of phase, or for larger phase changes we cannot predict whether they are in phase or out of phase, so in the worst case we expect a speckle-related intensity noise given by equation (4).

We conducted an experiment to obtain a plot of the correlation of interferograms corresponding to different wavelengths. The method adopted was to store a reference interferogram for an initial injection current value. The injection current was then stepped, causing a corresponding change in the phase, and a new interferogram was acquired. The second image was then subtracted from the reference, the result rectified and the average intensity of the resultant image calculated. The procedure was repeated until the interferometer phase had been changed by more than $2\pi$. When the phase shift equalled $\pi$ the averaged intensity attained its maximum value and when it was $2\pi$ the averaged intensity was a minimum; that is, subtracting from a speckle image an identical speckle image results in a ‘black’ (zero-intensity) image. A plot of average intensity against current is shown in figure 4.

![Figure 4. A plot of current against average intensity that maps the phase change of the interferometer with wavelength](image)

6. Discussion and Conclusion

Methods that have been proposed to reduce the effects of interference fringes include careful alignment of optical components or mechanically jittering the offending components. Evidence also suggests that in the right circumstances use of diffusely scattering materials may reduce fringes. We have investigated their use and the consequent introduction of random uncertainty associated with generation of laser speckle. We have developed a methodology for investigating the associated noise and presented preliminary data for a simulated gas cell.

Future work will involve investigating different diffusely reflecting materials and different optical path geometries including integrating spheres.

Acknowledgements

This work is supported by the Engineering and Physical Sciences Research Council (EPSRC), UK under grant No.GR/T04601/01. Jane Hodgkinson is supported by an EPSRC Advanced Fellowship, GR/T04595/01.

References

[1] Werle P 1998, Vol. 54 pp. 197-236.
[2] Sun H C and Whittaker E A. 1992 Vol. 31, No. 24 pp. 4998-5002.
[3] Silver J A and Stanton, A C 1988 Vol. 27, Appl. Opt (USA) pp. 1914-16.
[4] Tranchart S, Bachir I H and Destombes J-L 1996 Vol. 35 Appl. Opt (USA), pp. 7070-7074.
[5] Ennos A E 1975 Laser speckle and related phenomena : Springer-Verlag, pp 203-53.
[6] Jones R and Wykes C (1989) Holographic and Speckle Interferometry (2nd edition), Cambridge University Press, Cambridge, UK.
[7] Sirohi R S 2002 vol 43 Contemp Phys. (UK); Taylor & Francis pp161-180.