Electro-Optic Propagation
Through Highly Aberrant Media

A Thesis submitted to the University of Adelaide as a requirement for the degree of
Doctorate of Philosophy in Mechanical Engineering

by

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Preface

This document is the culmination of many years of study, and is the thesis submitted for the award of Doctoral of Philosophy. The topic of research is electro-optic propagation through highly aberrant media. The effect of a high temperature, high turbulence gas medium on the propagation of various laser beams is studied. The propagated beams are imaged using focal plane array cameras and the images analysed to determine spatial and temporal degradations. The work importantly supports the laser beam defense of aircraft. A better understanding of laser beam propagation through high temperature and turbulence regimes was needed to provide better assessment of the capability of on-board laser systems (DIRCM) to defend aircraft from infrared seeking missile attack when scenarios dictate that the laser beam must propagate through the jet engine exhaust gases. The work improves the understanding of laser beam propagation in high temperature and turbulence regions, thereby allowing better optimization of the operation and design of life-saving DIRCM systems.
Abstract

Infrared guided, or “heat seeking” missiles, have posed a threat to aircraft ever since their inception. However, the proliferation of man portable shoulder launching infrared guided missiles has increased the threat level against both military and civilian aircraft. Furthermore, advanced variants of the missiles are less susceptible to decoy against traditional countermeasures such as flares. To counter the threat, advances in laser technology have allowed the development of small, robust and powerful infrared lasers that have been developed into laser defence systems that can be fitted to aircraft. These systems, Directed InfraRed CounterMeasures (DIRCM), detect the incoming missile and direct modulated infrared energy, in the form of a laser beam, on to the missile sensor to disrupt the missile’s guidance.

The defence system works well in laboratory settings, and through normal atmosphere, but effects of a highly aberrant propagation path on the laser beam’s temporal and spatial quality need to be considered. In particular, scenarios may arise where the laser beam must pass through the hot, turbulent gases of the engine exhaust, the plume. Some initial system studies highlight the problem but have not reported on the individual effects of the various laser and flow parameters in this high temperature, high turbulence environment. Furthermore, laser beam propagation has traditionally been studied at atmospheric temperatures and often in the visible spectrum to support geodesy.

The thesis incorporates a system level study in collaboration with the Defence Science Technology Organisation, Australia, and the Defence Science and Technology Laboratories, UK. The study showed general properties of the propagation but did not allow detailed analysis of the effect of the various flow and beam parameters on the laser beam propagation.

To further contribute to the knowledge in this field, the thesis took a novel approach to the study of laser beam propagation by using an experimental apparatus to produce high temperature, high turbulent flows in the laboratory for the purpose of studying the laser beam degradation while
controlling flow and beam parameters. This approach allowed the individual effects of flow and beam parameters; such as turbulence intensity, eddy scales, species concentration, wavelength, beam diameter and temperature, to be isolated analysed.

High temperature turbulent flows were generated by combusting a lean mixture of hydrogen and air, while applying perforated plates of various hole diameters and blockage ratios to the jet nozzle to condition the flow. The resulting flow was traversed by 632.8 nm and 4.67 µm wavelength laser beams of varying beam diameter. The resultant laser beam was recorded using visible and infrared detecting focal plane array cameras. The temporal and spatial properties of the propagated beams were analysed and linked to the flow conditions. The flow was characterised in terms of integral length scale and turbulence intensity using Particle Image Velocimetry (PIV) as the diagnostic tool.

The study found temperature, eddy size, beam diameter and wavelength to be parameters that significantly affected the laser beam propagation. For example, the beam displacement, for both wavelengths, was found to increase as the beam diameter was decreased, closely following the inverse third root of the beam diameter. Further, there was a difference in beam displacement related to wavelength. It was found that the 632.8 nm beam would need to be 8/7ths times greater in diameter than the 4.67 µm beam to produce the same beam displacement variance.

The experiment has extended the data range used to develop existing models and has allowed correlations to be observed at the higher temperatures found typically in jet engine plumes. These results show existing models that link beam diameter and wavelength to beam displacement at these higher temperatures are still valid.

The role of path length, although seen to be significant, was not able to be quantified using the experimental set-up, while the presence of carbon dioxide was found through theory and measurement to not be significant at the wavelengths studied.
A significant finding of the work has been the quantifying of the effects of high temperature on laser beam propagation. New data has provided correlations between beam displacement and temperature. The change in the increase in beam displacement variance with high temperature was found to be related to the inverse square of temperature. Beam displacement variance tended towards an asymptote at around 600°C for both wavelengths studied. However it was notable that the beam displacement variance was found to be related to wavelength, with the visible beam exhibiting a notably greater variance than the infrared beam at temperatures above 400°C. The new correlations have shown beam displacement models need to represent the effects of wavelength. This is required for the displacement variance to be correctly modelled as the temperatures increase to levels found in a jet engine plume.

Measurements also showed that as temperature increased, mean and variance of the spot size and the irradiance variance all increased. This data is reported in the thesis and can be used to estimate the energy being directed onto the sensor of an incoming missile under various flow conditions.

The findings and approach presented in this thesis has meant the impact of hot turbulent exhaust flows on the propagation of the DIRCM laser beam can be confidently predicted under a range of conditions. These results provide certainty for those designing DIRCM systems.
Declaration

NAME: William Martin Isterling    PROGRAM: PhD

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Contents

Preface .......................................................................................................................... ii

Abstract ...................................................................................................................... iii-v

Declaration ................................................................................................................... vi

Acknowledgements ..................................................................................................... vii

1 Introduction ............................................................................................................. 1
  1.1 Importance of Lasers in Missile Defence Systems ............................................... 1
  1.2 The Research Problem ....................................................................................... 2
  1.3 Objective .......................................................................................................... 3
  1.4 Specific Aims .................................................................................................... 3
  1.5 Thesis Layout ................................................................................................... 4

2 Background Literature ............................................................................................ 7
  2.1 Introduction ....................................................................................................... 7
  2.2 Refractive Index ............................................................................................... 7
    2.2.1 Introduction .............................................................................................. 7
    2.2.2 Review of Refractive Index Calculations ................................................. 10
    2.2.3 Refractive Index of Exhaust Gases .......................................................... 23
    2.2.4 Summary ................................................................................................. 24
  2.3 Fluid Mechanics Overview ............................................................................... 25
    2.3.1 Introduction to Turbulence ..................................................................... 25
    2.3.2 Turbulence Length Scales ..................................................................... 30
    2.3.3 Grid or Perforated Plate Generated Turbulence .................................. 31
  2.4 Flow Measurement Techniques ....................................................................... 33
    2.4.1 Mie Scattering ....................................................................................... 34
    2.4.2 Rayleigh Scattering .............................................................................. 35
    2.4.3 Raman Scattering ................................................................................. 36
3.3.6 Near and Far Field Measurements ................................................................. 83
3.3.7 Radiometric Measurements ........................................................................... 85
3.4 Discussion ........................................................................................................... 89
3.4.1 Refractive Index Structure Size in the Plume .................................................. 91
3.5 Closing Remarks ............................................................................................... 92
4 Simple Jet Parametric Study ................................................................................. 93
4.1 Introduction ....................................................................................................... 93
4.2 Parametric Study Objectives ........................................................................... 93
4.3 Experimental Apparatus and Setup ................................................................. 94
4.4 Methodology ..................................................................................................... 97
4.4.1 Beam Spot Samples ...................................................................................... 98
4.4.2 Temperature and Water ............................................................................... 102
4.4.3 Carbon Dioxide ............................................................................................ 104
4.4.4 Turbulent Intensity and Eddy Size ............................................................... 104
4.4.5 Path Length .................................................................................................. 105
4.5 Flow Characterisation Study ............................................................................ 106
4.5.1 Seeding the Flow .......................................................................................... 107
4.5.2 Camera and Timing ....................................................................................... 109
4.5.3 Temperature Profiling .................................................................................. 111
4.6 Data Reduction ................................................................................................. 111
4.6.1 Data Error Analysis ...................................................................................... 112
4.6.2 Length Scale ................................................................................................. 114
4.6.3 Turbulence Intensity ..................................................................................... 116
4.7 Results ............................................................................................................... 116
4.7.1 Effect of Blockage Ratio .............................................................................. 117
4.7.2 Effect of Hole Diameter .............................................................................. 120
4.7.3 Effect of Path Length and Temperature ....................................................... 123
4.8 Summary .......................................................................................................... 133
5 Beam Propagation: Results and Analysis ............................................................. 135
5.1 Introduction ...................................................................................................... 135
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bibliography</td>
<td>205</td>
</tr>
<tr>
<td>Appendix A: Laser Beam Calculations</td>
<td>217</td>
</tr>
<tr>
<td>Appendix B: Determining Anomalous Dispersion Effects</td>
<td>227</td>
</tr>
<tr>
<td>Appendix B: Alternative Refractive Index Calculations</td>
<td>230</td>
</tr>
<tr>
<td>Appendix C: Reynolds Number Calculations</td>
<td>233</td>
</tr>
<tr>
<td>Appendix D: Statistical Considerations</td>
<td>235</td>
</tr>
<tr>
<td>Appendix E: Characterizing the Flow</td>
<td>241</td>
</tr>
<tr>
<td>Appendix F: HITRAN: CO₂ and H₂O Spectral Line Intensities</td>
<td>243</td>
</tr>
<tr>
<td>Appendix G: Examples of Spot Images</td>
<td>247</td>
</tr>
<tr>
<td>Appendix H: Publications Arising from This Thesis</td>
<td>257</td>
</tr>
</tbody>
</table>
List of Figures

Figure 1.1: A mid-infrared signature showing the extent of the exhaust effect [1].................................2

Figure 2.1: Change in calculated refractivity (defined as $10^6 (n-1)$) due to the 4.25686 µm and 4.27965 µm CO$_2$ absorption lines, calculated using 3% CO$_2$ per volume in air. .................................9

Figure 2.2: Kolmogorov's -5/3 power law, relating power to spatial frequency (Reproduced from Turbulence & Symmetry, Berkeley University [65]).................................................................................28

Figure 2.3: Schematic of Kolmogorov and von Karman power spectral densities. .............................29

Figure 2.4: Fringes at the point of intersection of two coherent beams [84]........................................36

Figure 2.5: Layout of a PIV System [84]. ............................................................................................38

Figure 2.6: Schematic to illustrate the focusing angle and the diffraction angle. The scattering disk is the scale size $l$ at which these angles are equal. ........................................................................41

Figure 2.7: Schematic of phase front distortion. ...................................................................................63

Figure 3.1: The Gnome 1200 engine showing the core and bypass nozzles...........................................68

Figure 3.2: Plan view schematic of the near-field experimental set-up for the jet engine study. ..........69

Figure 3.3: Plan view schematic of the far-field experimental set-up for the jet engine study. The radiometric measurement set-up is shown on the left, while the camera set-up is shown on the right. ....................................................................................................69

Figure 3.4: Engine Turbine Exit Temperature (TET) and Axial Thrust as a function of RPM [136] ....70

Figure 3.5: The set-up for measurements through the plume. ..............................................................73

Figure 3.6: Centroid motion for the laser beam propagating 0.5 metres from the nozzle at 90° in a turbojet configuration at different crossing heights and over a range of engine conditions. ............76

Figure 3.7: Centroid motion for the laser beam propagating 1 metre from the nozzle at 90° in a turbojet configuration at different crossing heights and over a range of engine conditions. ............76

Figure 3.8: Centroid motion for the laser beam propagating 1 metre from the nozzle at 90° at different crossing heights and over a range of engine conditions for the turbofan configuration. ............78
Figure 3.9: Centroid motion for the laser beam propagating 1 metre from the nozzle at 90° at different crossing heights and over a range of engine conditions for the turbojet configuration. ........................................ 78

Figure 3.10: Centroid motion for a turbofan (1:1 bypass) plume in the y-direction for different propagation heights and as a function of engine setting for a laser beam propagating 0.5 metres from the nozzle at 90° ............................................................................................................. 79

Figure 3.11: A typical plume temperature profile as a function of distance from the nozzle where the turbojet is at maximum continuous engine setting [136] ......................................................................................................................... 80

Figure 3.12: Low frequency measurements of turbulence spectrum ...................................................... 81

Figure 3.13: Measured centroid motion for different integration times at engine idle setting ............... 82

Figure 3.14: Measured centroid motion for different integration times at engine 20,000 RPM setting. ................................................................................................................................................... 82

Figure 3.15: Six consecutive laser pulses recorded with the jet off ........................................................ 84

Figure 3.16: Six consecutive laser pulses recorded with the jet at maximum RPM ............................... 84

Figure 3.17: Variation in pulse-to-pulse irradiance measured by the InSb radiometer for the engine off. ....................................................................................................................................................... 85

Figure 3.18: Variation in pulse-to-pulse irradiance measured by the InSb radiometer for the engine at maximum power .................................................................................................................................................. 86

Figure 3.19: Distribution of log(pulse irradiance) for the engine off condition calculated from radiometer data ......................................................................................................................................................... 86

Figure 3.20: Engine off log(pulse irradiance) calculated from camera data using 13x13 pixels ......... 87

Figure 3.21: Distribution of log(pulse irradiance) for the engine at maximum power calculated from radiometer data ....................................................................................................................................................... 87

Figure 3.22: Engine maximum log(pulse irradiance) calculated from camera data using 13x13 pixels. ......................................................................................................................................................... 88

Figure 3.23: Calculated refractivity of dry air as a function of temperature at 4.67 µm ....................... 90

Figure 3.24: Refractivity of dry air with 3% CO₂ at STP near the 4.3 µm absorption band ................. 90

Figure 4.1: Schematic of apparatus used to produce the high temperature turbulent flow ............... 94

Figure 4.2: Sketch of optical setup .............................................................................................................. 96
Figure 4.3: Two consecutive images of the 632.8 nm beam after propagating through a 3 mm iris and a turbulent zone at 800°C.

Figure 4.4: Two consecutive images of the 4.67 µm beam after propagating through a 3 mm iris and a turbulent zone at 800°C.

Figure 4.5: The left hand image depicts the raw image of the 4.67 µm beam captured after propagating through a 800°C flow. The right hand image is a corrected version of the left hand image; background subtraction and the 1/e² threshold has been applied.

Figure 4.6: Typical file showing standard deviation of centroid position as a function of the number of samples.

Figure 4.7: Calculated refractive index gradient at 632.8 nm and 4.67 µm over a range of temperatures and for the experimental conditions at the higher temperatures.

Figure 4.8: Schematic of the experimental layout used for Particle Image Velocimetry (PIV)

Figure 4.9: Diagram of the Seeder configuration.

Figure 4.10: A processed image, showing some saturation (inside white ring).

Figure 4.11: Graphical presentation of the calculated integral length scale. In this case the integral length scale was calculated from the curve fit to be 2.86 mm, being the area under the curve.

Figure 4.12: Temperature profile for blockage ratios 37%, 55% and 65%.

Figure 4.13: Integral length scales calculated for blockage ratios 37%, 55% and 65%.

Figure 4.14: The average velocity measured along a radial outwards from the axial core for the 37%, 55% and 65% blockage ratio cases at 500°C with 5 mm diameter holes.

Figure 4.15: The standard deviation of the instantaneous velocity plotted against radial distance for the 37%, 55% and 65% blockage ratio cases at 500°C with 5 mm diameter holes.

Figure 4.16: Turbulence intensity for blockage ratio cases 37%, 55% and 65% at 500°C with 5 mm diameter holes.

Figure 4.17: Temperature profile for hole diameters 3 mm, 6 mm and 8 mm at 500°C with ~50% blockage ratio.

Figure 4.18: Integral length scales calculated hole diameters 3 mm, 6 mm and 8 mm at 500°C with ~50% blockage ratio.
Figure 4.19: The average velocity measured along a radial outwards from the axial core for the 3 mm, 6 mm and 8 mm hole diameter cases at 500°C with ~50% blockage ratio. .................................................. 122

Figure 4.20: The standard deviation of the instantaneous velocity plotted against radial distance for the 3 mm, 6 mm and 8 mm hole diameter cases at 500°C with ~50% blockage ratio. .......................... 122

Figure 4.21: Turbulence intensity for hole diameter cases 3 mm, 6 mm and 8 mm at 500°C with ~50% blockage ratio........................................................................................................... 123

Figure 4.22: Temperature profiles at various heights above the nozzle for the same conditions. .... 124

Figure 4.23: Path length through the hot gases at various heights with the conditions fixed at the nozzle........................................................................................................................................... 125

Figure 4.24: Average temperature gradient each 2 mm path length step shown for various heights with the conditions fixed at the nozzle ........................................................................................................................................... 125

Figure 4.25: Integral length scale as a function of propagation height above the nozzle with the flow conditions at the nozzle the same for each case ........................................................................................................................................... 126

Figure 4.26: The average velocity measured along the flow axis with the flow conditions fixed at the nozzle........................................................................................................................................... 126

Figure 4.27: The average velocity measured along a radial outwards from the centre axis at heights above the nozzle of 5, 10, 15 and 25 times the 8 mm perforated plate hole diameter. .......................... 127

Figure 4.28: The standard deviation of the instantaneous velocity plotted against radial distance for heights above the nozzle of 5, 10, 15 and 25 times the 8 mm perforated plate hole diameter ............... 127

Figure 4.29: Turbulence intensity for heights above the nozzle of 5, 10, 15 and 25 times the 8 mm perforated plate hole diameter ............ 127

Figure 4.30: Temperature profiles at various heights with the peak temperature fixed at 300°C. .... 129

Figure 4.31: Path length through the hot gases at various heights with the peak temperature fixed at 300°C .................................................................................................................................................. 129

Figure 4.32: Average temperature gradient each 2 mm path length step shown for various heights with the peak temperature fixed at 300°C .................................................................................................................................................. 130

Figure 4.33: Integral length scale as a function of propagation height above the nozzle with the peak flow temperature fixed at 300°C at the various propagation heights .................................................................................................................................................. 131
Figure 4.34: The average velocity measured along a radial outwards from the centre axis at heights above the nozzle of 5, 10, 15 times the 8 mm perforated plate hole diameter with the temperature fixed at 300°C at the various heights.

Figure 4.35: The standard deviation of the instantaneous velocity plotted against radial distance for heights above the nozzle of 5, 10 and 15 times the 8 mm perforated plate hole diameter with the temperature fixed at 300°C at the various heights.

Figure 4.36: Turbulence intensity for heights above the nozzle of 5, 10 and 15 times the 8 mm perforated plate hole diameter with the temperature fixed at 300°C at the various heights.

Figure 5.1: Two consecutive images of the 632.8 nm beam (top) and 4.67 µm beam (bottom) having propagated through a 3 mm iris and a turbulent zone at 700°C. The contrast has been set to show any pixels with a value not zero as white. A threshold of 13.5% has been applied.

Figure 5.2: Measured standard deviation of centroid position for 632.8 nm and 4.67 µm beams, with beam diameter 3 mm, over a range of temperatures.

Figure 5.3: Theoretical refractive index calculated using Ciddor's equations for the gas conditions at each experimental point for the 632.8 nm and 4.67 µm beams.

Figure 5.4: Curve fit to measured standard deviation of centroid position for the 632.8 nm beam over a range of temperatures.

Figure 5.5: Curve fit to measured standard deviation of centroid position for the 4.67 µm beam over a range of temperatures.

Figure 5.6: Standard deviation of the visible beam’s centroid position calculated for various box areas placed each frame around that frames un-windowed calculated centroid position.

Figure 5.7: Normalized standard deviation of spot area for the 4.67 µm beam.

Figure 5.8: Normalized standard deviation of spot area for the 632.8 nm beam.

Figure 5.9: Spot area divided by standard deviation of spot area for the 4.67 µm beam.

Figure 5.10: Spot area divided by standard deviation of spot area for the 632.8 nm beam.

Figure 5.11: The average number of pixels containing counts that are over the 1/e² threshold plotted against the interrogation window size for the 4.67 µm beam. Normalisation is done by dividing the data for each temperature by the data obtained when traversing the beam through ambient room conditions with the gas flow off.
Figure 5.12: The average number of pixels containing counts that are over the $1/e^2$ threshold plotted against the interrogation window size for the 632.8 nm beam. Normalisation is done by dividing the data for each temperature by the data obtained when traversing the beam through ambient room conditions with the gas flow off................................................................. 146

Figure 5.13: The standard deviation of the number of pixels containing counts that are over $1/e^2$ threshold plotted against interrogation window size for the 4.67 µm beam. Normalisation is done by dividing the data for each temperature by the data obtained when traversing the beam through ambient room conditions with the gas flow off.................................................................................. 147

Figure 5.14: The standard deviation of the number of pixels containing counts over the $1/e^2$ threshold plotted against interrogation window size for the 632.8 nm beam. Normalisation is done by dividing the data for each temperature by the data obtained when traversing the beam through ambient room conditions with the gas flow off................................................................................................. 148

Figure 5.15: The standard deviation of pixel count at various integration window sizes for the 632.8 nm beam propagating through various turbulent gas temperatures. ................................................ 148

Figure 5.16: The standard deviation of pixel count at various integration window sizes for the 4.67 µm beam propagating through various turbulent gas temperatures. ...................................................... 149

Figure 5.17: Measured standard deviation of energy determined at various integration window sizes for the 4.67 µm beam propagating through various turbulent gas temperatures, normalized by the standard deviation of energy in the corresponding window sizes when the laser beam propagates through an ambient temperature gas. ................................................................. 150

Figure 5.18: Measured standard deviation of energy determined at various integration window sizes normalized to the standard deviation of energy in the smallest window size, for the 4.67 µm beam propagating through various turbulent gas temperatures. ................................................................. 151

Figure 5.19: Measured standard deviation of energy determined at various integration window sizes for the 632.8 nm beam propagating through various turbulent gas temperatures, normalized by the standard deviation of energy in the corresponding window sizes when the laser propagates through an ambient temperature gas. .................................................................................... 152

Figure 5.20: Measured standard deviation of energy determined at various integration window sizes normalized to the standard deviation of energy in the smallest window size, for the 632.8 nm beam propagating through various turbulent gas temperatures. ................................................................. 152

Figure 5.21: Average count per frame determined at various integration window sizes for the 632.8 nm (closed symbols) and 4.67 µm (open symbols) beams propagating through various turbulent gas temperatures, normalized by the average count per pixel in the corresponding window sizes when the laser propagates through an ambient temperature gas......................................................... 153
Figure 5.22: Average count per illuminated pixel calculated over a range of interrogation windows from a number of temperature measurements for the 632.8 nm beam.................................154

Figure 5.23: Average count per illuminated pixel calculated over a range of interrogation windows from a number of temperature measurement for the 4.67 µm beam.............................................154

Figure 5.24: Standard deviation of centroid position for 4.67 µm and 632.8 nm beams versus carbon dioxide percentage by volume in H₂ flame at constant temperature of 700°C..............................155

Figure 5.25: Calculated refractivity change due to 4.25686 and 4.27965 µm absorption lines in a 3% CO₂ per volume in air. ........................................................................................................157

Figure 5.26: The calculated effect of changing carbon dioxide levels in the gas on the refractive index gradient between dry air at 20°C and 700°C produced from combusting H₂ at 4.67 µm and 632.8 nm. ........................................................................................................158

Figure 5.27: Beam displacements of the 632.8 nm and 4.67 µm laser beams with diameters of 3 mm, 6 mm and 8 mm traversing the 500°C turbulent flow at a height of 85 mm above the 5 mm perforated plate at various plate solidities..............................................................................................159

Figure 5.28: Standard deviation of beam displacement versus perforated plate hole diameter for perforated plates with a blockage ratio ~50% with the 4.67 µm infrared and 632.8 nm visible laser beams and traversing the flow at a height of 85 mm above the nozzle and through a temperature of 500°C and 180°C respectively. ..............................................................................................160

Figure 5.29: The average standard deviation of beam displacement for the cases measured in Figure 5.28 plotted against the integral length scale determined for the flow conditions. .........................162

Figure 5.30: Beam displacement versus beam diameter for 632.8 nm and 4.67 µm beams with and without a 5 mm diameter perforated plate over the nozzle with a 55% blockage ratio................163

Figure 5.31: Standard deviation of centroid displacement of the 632.8 nm and 4.67 µm beam Three series of runs with temperature fixed at each position at 300°C, Perforated Plate 8mm at 53%. ......165

Figure 5.32: Standard deviation of centroid displacement of the 632.8 nm beam when traversing the flow at different heights above the nozzle with temperature decreasing with distance downstream. The nozzle exit temperature and flow conditions were fixed.................................165

Figure 6.1: A histogram of frame-to-frame irradiance (total count) distribution for the 632.8 nm beam propagating through low temperature gas. .................................................................182

Figure 6.2: A histogram of frame-to-frame irradiance (total count) distribution for the 632.8 nm beam propagating through high temperature gas.................................................................182
Figure 6.3: A histogram of frame-to-frame irradiance (total count) distribution for the 4.67 µm beam propagating through low temperature gas.

Figure 6.4: A histogram of frame-to-frame irradiance (total count) distribution for the 4.67 µm beam propagating through high temperature gas.

Figure 6.5: Three consecutive images of the 632.8 nm beam (top) and 4.67 µm beam (bottom), both having propagated through a 3 mm iris and a turbulent zone at 700°C. The contrast has been set to show any pixels with a value not zero as white. A threshold of 13.5% has been applied.

Figure 6.6: The beam displacement standard deviation averaged over all runs plotted against the turbulence intensity calculated as an integral of the turbulence intensity between the jet’s centre axis and the centre of the shear layer.
List of Tables

Table 2.1: A sample of refractive index formulations until the early 1970's. ..................................................13

Table 3.1: Jet engine experimental conditions........................................................................................................71

Table 3.2: Mean and standard deviation for the four Gaussian distributions. .........................................................88

Table 4.1: Perforated plate specifications.................................................................................................................95

Table 4.2: List of experimental runs and their parameters..........................................................................................98

Table 4.3: Showing volume fraction of water present in the flow at various temperatures for an equivalence ratio less than 1. ...........................................................................................................102

Table 5.1: Coefficients for the beam displacement fitting function.............................................................................140

Table 6.1: Laser beam movements reported in various jet engine beam propagation studies. ........175

Table 6.2: C_{n2} values computed from measured spot areas......................................................................................180