

University of Hertfordshire

Respirable Fibre Detection from Light Scattering Patterns

By

Rob Lewis

A thesis submitted to the University of Hertfordshire
in partial fulfilment for the degree of Doctor of Philosophy

August 2025

Abstract

Air-quality monitoring is essential in the reduction or prevention of potential respiratory problems and diseases. Many different instruments and techniques have been developed to detect and monitor different aerosol using light-scattering techniques in real time or close to it. The monitoring of respirable fibrous aerosol such as asbestos, however, is usually undertaken after filter collection taking around 24 hours for confirmation. Instruments have been developed for the detection of asbestos and other fibrous aerosol but perform poorly compared to filter analysis. Additionally, many of these instruments are costly or unavailable and mostly operate using ensemble scattering with additional methods other than the analysis of only scattered light. This project investigates the spatial light scattering from fibres and cylindrical objects using both modelled and captured data to develop single fibre measurement techniques using only forward scattered light.

What was found is that the diameter, length, orientation, and refractive index of the scattering objects all contribute to changes in the forward scattered light that could be measured and used to determine the size. Different archetypical features of the scattering patterns were identified by analysing modelled data from varying input parameters, these features were then used as a reference for the measurement of other scattering patterns produced by fibrous aerosol. Due to the complexity of this problem, thorough investigations were limited to length and diameter measurements for fibres reasonably aligned with the incident radiation; orientation was investigated but not to the extent of the size measurements. Furthermore, fibre curvature was shown to affect the scattered light beyond the abilities of the developed measurement systems.

The results indicated that a reasonably accurate measurement of the fibre could be made using only the forward scattered light. This was tested using both a simulated Monte-Carlo-based experiment and using data from captured scattering images and comparing the size distributions to microscopy data. Overall, both experiments showed positive results. The simulated Monte-Carlo-based experiment showed that most measurements produced a reasonable size, depending on refractive index: the lower the absorption coefficient, the further from the true size. Outliers were also identified as results of the reference measurement system. At the extreme limits of the reference data, the interpolation of the sizes resulted in obvious mismeasurements. The captured data and the microscopy data showed good visual comparisons in the size distributions. An alternative length measurement was required due the wild inaccuracy at first but showed a marked improvement when a new system was used. Additionally, some of the outliers in the modelled experiment reflected that in the aerosol experiment results. Inconsistencies were found in the size distribution comparisons for similar size ranges.

This is an indication into the possibility of a low-cost monitoring system, more accessible and accurate than the current instruments, that could be developed using the research within this project.

Acknowledgements

This work is dedicated to the memory of my beloved grandfather Donald “Don” Charles Ranells, the sweetest, kindest soul who greatly supported me throughout my academic journey. He gave me a place to live during my undergraduate degree and supplied endless conversation and beers during this project, which he was always fascinated by.

I want to thank my supervisors for their endless support throughout this project, it has been a fascinating experience that wouldn’t have been the same without you. Chris, for letting me crash on his floor whilst looking for a flat and putting up with my bad language. Richard, for the endless conversations about music, literature, history, and all manner of topics that served as a brief distraction. Sean for the invaluable advice and support. Bill and Adrian for their fantastic help. And Sheena, for the help with a better understanding of immunology and the moral support via email. I also want to thank the rest of the PID group for their support, advice, and entertainment (Skhathi), it has been a delight to work with you all.

For helping me out in the lab, beers after work, and making bad cider, I want to thank Jess; both my work life and social life was never the same after you moved. Harry, for putting up with me in the office and the several meetings about coding for Chapter 2; I could not have completed this chapter without his help. And my dear friend Altin, for keeping me sane with the moral support, endless coffee breaks and pub trips, Bristol shenanigans, tinnies in the park, and late-night street karaoke!

I want to thank the Aerosol Science CDT team for the organisation of the courses, webinars, workshops, and conferences; the experiences and opportunities were invaluable. Also, the 2nd CDT cohort for all the help with the courses and tolerating me during lockdown. Especially Fred the Scrabble master. Toria from the 1st cohort, for the moral support and being generally lovely. And Darragh and Laura, for their kindness and the occasional pub visit.

For the overall support, both moral and otherwise, I want to thank Ian; our morning chats, moaning about life, kept me from going completely mental. I also want to thank the rest of the MEMS group, a lovely bunch who were always happy to help me.

Other thanks to my old office buddy Avi, Veto for the banter and chats about films, Bear for the painting and bass guitar encouragement, my flatmate Kasia for putting up with me for three and a half years, and Rob for the occasional taxi service. The rest of the usual pub crowd also helped keep my sanity: Gözde, Elif, Daisy, Aiden, Jamie, and Tom. I also want to thank my undergraduate tutor Reto, who encouraged me to apply for this project.

I want to thank my family for their unending help; I am privileged to have such a loving, supportive family and without their support I would not have been able to do this. My mum, for the hotel privileges, lasagne requests, and listening to me rant down the phone. My dad, for all of his pot noodles. Noo, for the pub trips, dog walks, and tortoise cuddles. Addam, for constantly making fun of me. Maz, my occasional driving buddy. And Paul, for the birthday pub crawls.

I also want to thank my friends back home for their support and encouragement. Dean and Britt, the nicest of humans; for putting up with me more than my parents, hanging out in the shed, and off-season BBQs. Bayels and Steve, for making my problems seem trivial. My nerds: Connor, Tom, Tony, Fil, and Tally; for the games, online chats, and the yearly Nottingham pilgrimage. Also, Dave for attempting to read this. And finally, Hannah, because she’s awesome.

ABSTRACT	I
ACKNOWLEDGEMENTS	II
LIST OF FIGURES	VII
LIST OF TABLES	XVI
ABBREVIATIONS	XVII
1 INTRODUCTION	1
1.1 A QUICK HISTORY	1
1.2 HEALTH	1
1.2.1 <i>Effects of Respirable Fibres</i>	1
1.2.1.1 Macro-Effects	1
1.2.1.2 Micro-Effects	2
1.2.2 <i>Deposition Mechanisms</i>	2
1.2.2.1 Inhalation and Aerosol Deposition	2
1.2.2.2 Fibre Dynamics	4
1.2.3 <i>Sources of Fibres</i>	5
1.2.3.1 Asbestos Exposure	5
1.2.3.2 Non-Asbestos Exposure	5
1.2.3.3 Micro-Machined Fibres	6
1.2.4 <i>Regulations</i>	6
1.2.4.1 WHO/NIOSH Regulations	6
1.2.4.2 Interlaboratory Comparisons	7
1.3 INSTRUMENTATION	8
1.3.1 <i>Basic Aerosol Monitoring</i>	8
1.3.2 <i>Optical-Based Particle Counters</i>	9
1.3.2.1 OPC Working Mechanisms	9
1.3.2.2 Extended Size Ranges	10
1.3.3 <i>Bio-Detection</i>	12
1.3.4 <i>Fibre Monitors</i>	12
1.3.4.1 Electrostatic Alignment	12
1.3.4.2 Multi-Fibre Light Scattering	13
1.3.4.3 Single-Fibre Magnetic Alignment	14
1.3.5 <i>Spatially Resolved Light Scattering Instruments</i>	14
1.3.5.1 Working Principles	14
1.4 OVERVIEW OF THESIS	16
1.5 FORMALISMS	17
1.5.1 <i>Light Scattering Definitions</i>	17
1.5.2 <i>Babinet's Principle</i>	17
1.5.3 <i>Maxwell's Equations</i>	18
1.5.4 <i>Stokes Vector & Mueller Matrix</i>	19
1.5.5 <i>Scattering Angles</i>	21
1.5.6 <i>Euler Angles</i>	21
2 SIMULATIONS	24
2.1 INTRODUCTION	24
2.2 MODELLING WITH DIFFRACTION THEORY	24
2.2.1 <i>Classical Diffraction Theory</i>	24
2.2.1.1 Background	24
2.2.1.2 Theory	24
2.2.1.3 Example diffraction patterns	26
2.2.1.3.1 One-Dimensional Diffraction Patterns	26
2.2.1.3.2 Two-Dimensional Diffraction Patterns	27
2.2.1.4 Limitations	28

2.2.2	<i>Fourier Optics Model of Diffraction</i>	28
2.2.2.1	Background	28
2.2.2.2	Theory	29
2.2.2.3	Application	30
2.2.2.3.1	One-Dimensional	30
2.2.2.3.2	Two-Dimensional	30
2.2.2.4	Limitations	31
2.3	LORENZ-MIE THEORY	31
2.3.1	<i>Background</i>	31
2.3.2	<i>Theory</i>	31
2.3.2.1	Basics	31
2.3.2.2	Generalised Lorenz-Mie Theory for Infinite Cylinders	32
2.3.2.3	Finite Cylinders	32
2.3.3	<i>Application</i>	32
2.3.4	<i>Limitations</i>	34
2.4	T-MATRIX	34
2.4.1	<i>Overview</i>	34
2.4.2	<i>Application</i>	34
2.4.3	<i>Limitations</i>	36
2.5	DISCRETE DIPOLE APPROXIMATION	37
2.5.1	<i>Overview</i>	37
2.5.2	<i>Example Models</i>	37
2.5.3	<i>Limitations</i>	40
2.6	RAY TRACING WITH DIFFRACTION ON FACETS	41
2.6.1	<i>Overview</i>	41
2.6.2	<i>Application</i>	41
2.6.3	<i>Limitations</i>	42
2.7	PARENT BEAM TRACER	42
2.7.1	<i>Overview</i>	42
2.7.2	<i>Application</i>	43
2.7.3	<i>Limitations</i>	43
2.8	COMPARING METHODS	44
2.8.1	<i>Selecting Candidate Scattering Models</i>	44
2.8.2	<i>Comparing the Three Candidate Methods</i>	44
2.9	ADDA OPTIMISATION	46
2.10	CONCLUSION	48
3	STATIC FIBRE EXPERIMENT	49
3.1	INTRODUCTION	49
3.1.1	<i>Motivation</i>	49
3.1.2	<i>Similar Experiments</i>	49
3.1.2.1	Review	49
3.1.2.2	Discussion	50
3.1.3	<i>Considerations to the Following Experiment</i>	50
3.2	EQUIPMENT	51
3.2.1	<i>Instrumentation</i>	51
3.2.1.1	Available Equipment	51
3.2.1.2	In-House Manufacturing	51
3.2.2	<i>Samples</i>	54
3.2.2.1	Justification of Samples	54
3.2.2.2	Carbon Fibre	54
3.2.2.3	Glass Fibre	55
3.3	METHOD	56
3.3.1	<i>Set-Up</i>	56

3.3.1.1	Equipment Layout	56
3.3.1.2	Sample Mounting	57
3.3.1.3	Focusing	57
3.3.1.4	Alignment	58
3.3.2	<i>Data Acquisition</i>	58
3.3.2.1	Measurements	58
3.3.2.2	Calibration	59
3.3.2.3	Limitations	59
3.4	RESULTS	59
3.4.1	<i>Carbon Fibre</i>	59
3.4.2	<i>Glass Fibre</i>	60
3.5	COMPARISON OF RESULTS WITH MODELS	61
3.5.1	<i>Carbon Fibre</i>	62
3.5.1.1	Comparison with Simulations	62
3.5.1.2	Limitations	63
3.5.2	<i>Glass Fibre</i>	64
3.5.2.1	Refractive Index Problem	64
3.5.2.2	Comparison with Simulations	66
3.5.2.3	Limitations	68
3.6	CONCLUSIONS	69
4	FIBRE CHARACTERISATION FROM THEORETICAL LIGHT SCATTERING PATTERNS	71
4.1	INTRODUCTION	71
4.2	PARAMETERS INVESTIGATED	71
4.2.1	<i>Diameter</i>	71
4.2.1.1	Parameters Changed	71
4.2.1.2	Changes in Measurement Metrics	73
4.2.2	<i>Length</i>	74
4.2.2.1	Parameters Changed	74
4.2.2.2	Changes in Measurement Metrics	75
4.2.3	<i>Length/Diameter Dependence</i>	76
4.2.3.1	Parameters Changed	76
4.2.3.2	Changes in Measurement Metrics	77
4.2.4	<i>Orientation Dependence</i>	78
4.2.4.1	Parameters Changed	78
4.2.4.2	Orientation Clarification	80
4.2.4.3	Changes in Measurement Metrics	80
4.2.5	<i>Refractive Index</i>	83
4.2.5.1	Parameters Changed	83
4.2.5.2	Changes in Measurement Metrics	84
4.2.6	<i>Curvature</i>	87
4.3	MONTE CARLO-BASED EXPERIMENT	88
4.3.1	<i>Method</i>	89
4.3.1.1	Parameters	89
4.3.1.2	Reference Data	90
4.3.1.3	Randomised Data	90
4.3.1.4	Features	90
4.3.2	<i>Results</i>	93
4.3.2.1	Diameter	93
4.3.2.2	Length	97
4.3.2.3	Investigating Outliers	98
4.4	DISCUSSION	100
4.5	OPTIMISATION	101
4.5.1	<i>Gradient Measurements</i>	101
4.5.2	<i>Refractive Index</i>	102
4.6	CONCLUSION	104

5	EXPERIMENTAL VERIFICATION	106
5.1	INTRODUCTION	106
5.1.1	<i>Motivation</i>	106
5.1.2	<i>Similar Work</i>	106
5.2	EQUIPMENT	106
5.2.1	<i>Experimental Setup</i>	106
5.2.2	<i>Samples</i>	108
5.3	METHOD	111
5.3.1	<i>Sample Aerosolisation</i>	111
5.3.2	<i>Contamination Considerations</i>	111
5.3.3	<i>Measurements</i>	112
5.3.3.1	Reference Data	112
5.3.3.2	Measured Light Scattering Features	113
5.3.3.3	Microscopy Measurements	119
5.3.3.4	Errors	120
5.4	RESULTS	124
5.4.1	<i>Light Scattering</i>	125
5.4.1.1	Analysis of Scattering Patterns	125
5.4.1.2	Limitations/Problems	127
5.4.1.3	Rejected Image Data	128
5.4.2	<i>Optical Microscopy</i>	129
5.4.2.1	Sample-Typical Size Distributions	129
5.4.2.2	Limitations/Problems	131
5.4.3	<i>Comparisons</i>	132
5.4.3.1	Diameters	132
5.4.3.2	Lengths	133
5.4.3.3	Limitations/Problems	133
5.4.3.4	Statistical Analyses	140
5.5	DISCUSSION	142
5.6	CONCLUSION	143
6	CONCLUSIONS AND FUTURE WORK	146
6.1	PROJECT CONCLUSIONS	146
6.1.1	<i>Strengths</i>	146
6.1.2	<i>Limitations</i>	146
6.1.3	<i>Future work</i>	147
6.2	INSTRUMENTATION DESIGN – WHAT CAN BE ACHIEVED	149
	BIBLIOGRAPHY	152
7	APPENDIX	163
7.1	FOURIER TRANSFORM EXPLANATION	163
7.2	STATIC FIBRE EXPERIMENT RESULTS	165
7.3	CHAPTER 4 SUPPLEMENTARY	167
7.4	SOFTWARE AND ALGORITHM DESCRIPTION	170
7.4.1	<i>Image Processing</i>	170
7.4.1.1	Modelled Data	170
7.4.1.2	PPD Data	171
7.4.1.3	Curve Fitting Algorithm	173
7.4.1.4	Image Categorisation	174
7.4.2	<i>Measurements</i>	175
7.4.2.1	Processing Data	175
7.4.2.2	Determining Measurements	175
7.5	CHAPTER 5 SUPPLEMENTARY RESULTS	175
7.6	EXTRA IMAGE ANALYSIS	176

List of Figures

FIGURE 1.1: ILLUSTRATION OF THE HUMAN RESPIRATORY SYSTEM, HIGHLIGHTING THE EXTRATHORACIC, TRACHEOBRONCHIAL, AND PULMONARY REGIONS. ADAPTED FROM NATIONAL CANCER INSTITUTE (2001).	4
FIGURE 1.2: EXPERIMENTAL (TOP ROW) SCATTERING AND MODELLED (BOTTOM ROW) DATA FROM A CUBE, DOUBLET, DROPLET, AND A MICRO-MACHINED FIBRE (LEFT TO RIGHT), ADAPTED FROM HIRST & KAYE (1996).	15
FIGURE 1.3: SCATTERING IMAGES CAPTURED, SHOWING BACKGROUND LABORATORY AIR (TOP ROW) AND IDENTIFIED AS IRREGULAR DUST (LARGE AND SMALL), FLAKE, WATER DROPLET, AND A SALT CRYSTAL (LEFT TO RIGHT). THE MIDDLE ROW SHOWS SCATTERING EXAMPLES OF CROCIDOLITE ASBESTOS AND THE BOTTOM ROW CHRYSOTILE ASBESTOS. ADAPTED FROM P. H. KAYE (1998).	16
FIGURE 1.4: ILLUSTRATION OF DIFFERENT LIGHT SCATTERING PROCESSES.	17
FIGURE 1.5: GRAPHICAL EXPLANATION OF BABINET'S PRINCIPLE; THE TOP LEFT SHOWS A 2D SQUARE APERTURE AND THE TOP RIGHT SHOWS THE COMPLIMENTARY SHAPE, BELOW ARE THE RESULTING DIFFRACTION PATTERNS OF BOTH.	18
FIGURE 1.6: GRAPHICAL REPRESENTATION OF THE POLARISATION ELEMENTS OF A STOKES VECTOR. THE TOP ROW SHOWS THE POLARISATION OF LIGHT FOR A POSITIVE VALUE AND THE BOTTOM ROW FOR NEGATIVE. THE DIRECTION OF THE POLARISATION IS INDICATED BY THE GREEN ARROWS.	20
FIGURE 1.7: GRAPHICAL EXPLANATION OF SCATTERING ANGLES θ AND ϕ USING A CYLINDER WITH ITS MAJOR AXIS PERPENDICULAR TO THE INCIDENT LIGHT PROPAGATION DIRECTION AS AN EXAMPLE.	21
FIGURE 1.8: REFERENCE FRAME FOR EULER ANGLES EXPLANATION – INITIAL STATE, NO ROTATION.	22
FIGURE 1.9: REFERENCE FRAME FOR EULER ANGLES EXPLANATION – INITIAL ROTATION ABOUT THE Z AXIS BY α° .	22
FIGURE 1.10: REFERENCE FRAME FOR EULER ANGLES EXPLANATION – SECOND ROTATION ABOUT THE LINE OF NODES (N) BY β° .	22
FIGURE 1.11: REFERENCE FRAME FOR EULER ANGLES EXPLANATION – FINAL ROTATION ABOUT THE z AXIS BY γ° .	23
FIGURE 1.12: EXAMPLE OF A CYLINDER ORIENTATED AT AN EULER ANGLE OF 0, 90, 0 (CENTRE). THE RIGHT IMAGE SHOWS THE MODELLED 90° FORWARD SCATTERING OF A CYLINDER WITH THE SAME ORIENTATION. THE LEFT IMAGE SHOWS LIGHT SCATTERING DATA CAPTURED BY PPD2 OF A FIBRE OF SIMILAR ORIENTATION.	23
FIGURE 2.1: GRAPHICAL REPRESENTATION OF SINGLE SLIT DIFFRACTION.	25
FIGURE 2.2: RESULTANT, NORMALISED DIFFRACTION PATTERN FROM SINGLE SLIT INTERFERENCE OF WIDTHS $0.75\ \mu\text{M}$ (BLUE) AND $2.5\ \mu\text{M}$ (ORANGE).	26
FIGURE 2.3: GRAPHICAL REPRESENTATION OF THE RELATIONSHIP BETWEEN THE FIRST MINIMUM OF SINGLE SLIT DIFFRACTION PATTERNS AND THE CORRESPONDING WIDTH OF THE SLIT.	27
FIGURE 2.4: THE VECTOR OUTER PRODUCT OF TWO SINGLE SLIT DIFFRACTION PATTERNS OF WIDTHS $0.75\ \mu\text{M}$ AND $2.5\ \mu\text{M}$.	28
FIGURE 2.5: SQUARE PULSES (LEFT) PLOTTED AS REPRESENTATIONS OF A ONE-DIMENSIONAL OBJECT OR SLIT AND THEIR RESULTANT FOURIER TRANSFORMS (RIGHT) FOR PULSE SIZED OF $0.75\ \mu\text{M}$ AND $2.5\ \mu\text{M}$.	30
FIGURE 2.6: A RECTANGULAR PULSE (LEFT) OF DIMENSIONS $0.75\ \mu\text{M}$ BY $2.5\ \mu\text{M}$ AND THE RESULTANT TWO-DIMENSIONAL FOURIER TRANSFORM (RIGHT).	31
FIGURE 2.7: SCATTERING PATTERNS GENERATED USING MIE THEORY FOR INFINITELY LONG CYLINDERS OF DIAMETERS $0.75\ \mu\text{M}$ AND $2.5\ \mu\text{M}$. THE LEFT SHOWS THE RESULTS FROM A CYLINDER OF REFRACTIVE INDEX $1.5+0.5i$ AND THE RIGHT $1.5+5E-6i$.	33
FIGURE 2.8: THE VECTOR OUTER PRODUCTS OF AN INFINITELY LONG $0.75\ \mu\text{M}$ DIAMETER CYLINDER AND A $10\ \mu\text{M}$ WIDE SLIT TO APPROXIMATE THE SCATTERING FROM A FINITELY LONG CYLINDER OF REFRACTIVE INDICES $1.5+0.5i$ (LEFT) AND $1.5+5E-6i$ (RIGHT).	33
FIGURE 2.9: SCREENSHOT OF THE SScATT SOFTWARE SHOWING THE PARTICLE GENERATION PROCEDURE FOR A SUPERELLIPSOID OF A 1.2 ASPECT RATIO.	35
FIGURE 2.10: SCREENSHOT OF THE SScATT SOFTWARE WITH THE T-MATRIX SCATTERING RESULTS OF THE OBJECT SHOWN IN FIGURE 2.9.	36
FIGURE 2.11: RESULTS OF THE S_{11} SCATTERING OF THE MUELLER MATRIX GENERATED BY ADDA FOR $0.75\ \mu\text{M}$ DIAMETER AND $10\ \mu\text{M}$ LONG CYLINDERS. THE RIGHT SHOWS THE RESULTS OF THE CYLINDER OF REFRACTIVE INDEX $1.5+0.5i$, THE LEFT $1.5+5E-6i$. THIS IS HOW THE DATA IS GIVEN BY ADDA, AFTER SOME REARRANGING.	38
FIGURE 2.12: ADDA SCATTERING RESULTS OF THE FORWARD (FIRST 90° OF THE ϕ SCATTERING ANGLE) AND BACK (90° - 180° OF THE ϕ SCATTERING ANGLE) LIGHT SCATTERING FROM $0.75\ \mu\text{M}$ DIAMETER AND $10\ \mu\text{M}$ LONG CYLINDERS OF REFRACTIVE INDEX $1.5+0.5i$ (LEFT) AND $1.5+5E-6i$ (RIGHT).	38

FIGURE 2.13: ADDA LIGHT SCATTERING RESULTS OF A 0.75 μm DIAMETER AND 10 μm LONG CYLINDER OF REFRACTIVE INDEX $1.5+0.5i$, THE SAME AS THAT OF FIGURE 2.12 FOR THE FORWARD AND BACK SCATTERING IMAGES (RIGHT). LEFT SHOWS THE “SCATTERING SPHERE”, A MORE REPRESENTATIVE REPRESENTATION OF THE RESULTS.	39
FIGURE 2.14: COMPARISON OF THE ADDA RESULTS BEFORE AND AFTER TRANSFORMING RESULTANT SCATTERING MATRIX FROM SQUARE TO CIRCULAR FOR REFRACTIVE INDICES $1.5+0.5i$ (LEFT) AND $1.5+5E-6i$ (RIGHT). THE EXAMPLE USED WAS THAT OF A 0.75 μm DIAMETER BY 10 μm LONG CYLINDER AND A CONSTANT ANGULAR VALUE OF $\theta = 0^\circ$ WAS USED.	40
FIGURE 2.15: RTDF 90° FORWARD LIGHT SCATTERING RESULTS OF A 0.75 μm DIAMETER BY 10 μm LONG CYLINDER OF REFRACTIVE INDICES $1.5+0.5i$ (RIGHT) AND $1.5+5E-6i$ (LEFT).	41
FIGURE 2.16: RTDF SCATTERING RESULTS FROM A 0.75 μm DIAMETER BY 10 μm LONG CYLINDER OF REFRACTIVE INDEX $1.5+5E-6i$ AT AN EULER ANGLE OF (0, 20, 0). THE RIGHT IMAGE SHOWS THE SCATTERING WHEN USING THE WAVELENGTH THROUGHOUT, 532NM, AND THE LEFT SHOWS THE RESULT FROM USING A 10 NM WAVELENGTH.	42
FIGURE 2.17: PBT SCATTERING RESULTS OF THE FORWARD (FIRST 90° OF THE φ SCATTERING ANGLE) AND BACK (90° - 180° OF THE φ SCATTERING ANGLE) LIGHT SCATTERING FROM 0.75 μm DIAMETER AND 10 μm LONG CYLINDERS OF REFRACTIVE INDEX $1.5+0.5i$ (LEFT) AND $1.5+5E-6i$ (RIGHT).	43
FIGURE 2.18: 90° FORWARD SCATTERING RESULTS FROM A 0.75 μm DIAMETER BY 10 μm LONG CYLINDER FROM ADDA (LEFT), GLMT (MIDDLE), AND DT (RIGHT). THE TOP ROWS CORRESPOND TO A REFRACTIVE INDEX OF $1.5+0.5i$ AND THE BOTTOM $1.5+5E-6i$ UNLESS OTHERWISE STATED.	45
FIGURE 2.19: HORIZONTAL (RIGHT) AND VERTICAL (LEFT) COMPONENTS OF THE FORWARD SCATTERING RESULTS FROM A 0.75 μm DIAMETER BY 10 μm LONG CYLINDER FROM ADDA (BLUE), GLMT (YELLOW DASHED), AND DT (ORANGE). THE TOP ROWS CORRESPOND TO A REFRACTIVE INDEX OF $1.5+0.5i$ AND THE BOTTOM $1.5+5E-6i$.	46
FIGURE 2.20 : ADDA SCATTERING RESULTS OF A 4 μm DIAMETER BY 20 μm LONG CYLINDER OF REFRACTIVE INDEX $1.45+0.0035i$ USING DIFFERENT ITERATIVE SOLVERS (ITR) AND STOPPING CRITERION VALUES (EPS) FOR COMPARISON.	47
FIGURE 2.21: THE DIFFERENCE IN MINIMUM COMPARED WITH THE DEFAULT SETTINGS FROM THE ADDA SCATTERING RESULTS OF A 4 μm DIAMETER BY 20 μm LONG CYLINDER OF REFRACTIVE INDEX $1.45+0.0035i$ USING DIFFERENT ITERATIVE SOLVERS (ITR) AND STOPPING CRITERION VALUES (EPS) FOR COMPARISON.	48
FIGURE 3.1: 3D RENDERS OF THE FIBRE MOUNT STL FILES, THE LONG CYLINDER INDICATES THE POSITION OF THE LASER AND THE ARROW INDICATES THE LOCATION OF WHERE THE FIBRE IS LOCATED. (NUTS AND BOLTS INCLUDED FOR INSTRUCTIVE PURPOSES, NOT ACTUALLY PRINTED).	52
FIGURE 3.2: 3D RENDERS OF THE PMT MOUNT AND SHUTTER STL FILES. BOTH THE 3D PRINTED PARTS AND THE PMT ARE BOLTED TOGETHER THROUGH THE FOUR HOLES, THE CIRCULAR SHUTTER ROTATES ABOUT A HINGE TO PROTECT THE PMT WHEN NOT IN USE.	52
FIGURE 3.3: 3D RENDERS OF THE LASER MOUNT STL FILE. DESIGNED TO FIT TO A STANDARD 1" CAGE PLATE ADAPTOR, THE LASER IS HELD IN POSITION BY TWO PINCH BOLTS.	53
FIGURE 3.4: 3D RENDERS OF THE BEAM-STOP STL FILE. A SMALL MIRROR IS GLUED TO THE 45° ANGLE OF THE SMALLER CAP, WHERE THE BEAM IS DIVERTED TO MINIMISE STRAY SCATTERING.	53
FIGURE 3.5: DIAGRAM OF ALUMINIUM ALIGNMENT TOOL.	54
FIGURE 3.6: SEM IMAGE OF CARBON FIBRE SAMPLE.	54
FIGURE 3.7: SEM IMAGE OF GLASS FIBRE SAMPLE. TOP FIBRE USED FOR THIS EXPERIMENT.	55
FIGURE 3.8: PHOTOGRAPH OF EXPERIMENTAL SETUP (TOP), INCLUDING LABELS AND PART OF THE ALIGNMENT PROCESS (BOTTOM).	56
FIGURE 3.9: EXPERIMENTAL LAYOUT DIAGRAM.	57
FIGURE 3.10: PHOTOGRAPHS OF THE PREPARED CARDBOARD MOUNT (LEFT), THE MOUNTED FIBRE IN THE CARBOARD MOUNT (MIDDLE), AND THE FIBRE MOUNTED IN THE 3D PRINTED MOUNT (RIGHT).	57
FIGURE 3.11: LIGHT SCATTERING RESULTS FROM CARBON FIBRE SAMPLE SHOWN ON A LOGARITHMIC SCALE FOR THE POWER, PLOTTED AGAINST SCATTERING ANGLE. THE FORWARD SCATTERING (FS), SIDE SCATTERING (SS), AND BACK SCATTERING (BS) REGIONS ARE SHADED BLUE, RED, AND GREEN RESPECTIVELY.	60
FIGURE 3.12: LIGHT SCATTERING RESULTS FROM GLASS FIBRE SAMPLE SHOWN ON A LOGARITHMIC SCALE FOR THE POWER, PLOTTED AGAINST SCATTERING ANGLE. THE FORWARD SCATTERING (FS), SIDE SCATTERING (SS), AND BACK SCATTERING (BS) REGIONS ARE SHADED BLUE, RED, AND GREEN RESPECTIVELY.	61
FIGURE 3.13: SCATTERING RESULTS OF CARBON FIBRE SCATTERING EXPERIMENT COMPARED WITH RESULTS OF MODELS PLOTTED ON A LOGARITHMIC SCALE FOR THE POWER AGAINST THE SCATTERING ANGLE. THE FORWARD SCATTERING	

(FS), SIDE SCATTERING (SS), AND BACK SCATTERING (BS) REGIONS ARE SHADED BLUE, RED, AND GREEN RESPECTIVELY. THE SCATTERING ANGLE IS LIMITED TO 60° , BUT COMPLETE RESULTS ARE FOUND IN APPX. 7.2.	62
FIGURE 3.14: DIFFERENCES IN THE ANGULAR LOCATIONS, IN COMPARISON TO THE MEASURED CARBON FIBRE DATA (ORANGE), FOUND FROM THE DIFFERENT MODELS USED. THE RIGHT SHOWS TO THE ORDER OF 13, THE LEFT 5. THE GENERALISED LORENTZ-MIE THEORY (GLMT) IS IN GREEN, THE AMSTERDAM DISCRETE DIPOLE APPROXIMATION (ADDA) IS IN BLUE, AND DIFFRACTION THEORY (DT) IS IN PURPLE.	63
FIGURE 3.15: SCATTERING PATTERN OF THE MEASURED DATA (ORANGE), ALONGSIDE THE GLMT RESULTS OF A CYLINDER OF $5.2\ \mu\text{M}$ DIAMETER (GREEN) WITH THE REFRACTIVE INDEX OF SILICON-DIOXIDE. THE FORWARD SCATTERING (FS), SIDE SCATTERING (SS), AND BACK SCATTERING (BS) REGIONS ARE SHADED BLUE, RED, AND GREEN RESPECTIVELY.	64
FIGURE 3.16: REFRACTIVE INDEX FINDING PROCESS. LEFT SHOWS A HEATMAP OF THE AVERAGE DIFFERENCE OF THE FIRST FOUR MINIMUM LOCATIONS OF THE GLMT-MODELLED DATA, DEPENDING ON REFRACTIVE INDEX. RIGHT SHOWS THE COMPARISON OF THE LAB-COLLECTED DATA (ORANGE) AND THE GLMT-MODELLED DATA OF THE REFRACTIVE INDEX WITH THE SMALLEST DIFFERENCE.	65
FIGURE 3.17: EXAMPLES OF THE VISUAL COMPARISONS MADE WITH THE MEASURED GLASS FIBRE SCATTERING DATA (ORANGE) AND THE GLMT MODELLED DATA (BLUE) TO VISUALLY FIND AN APPROPRIATE REFRACTIVE INDEX.	66
FIGURE 3.18: SCATTERING RESULTS OF GLASS FIBRE SCATTERING EXPERIMENT COMPARED WITH RESULTS OF MODELS PLOTTED ON A LOGARITHMIC SCALE FOR THE POWER AGAINST THE SCATTERING ANGLE. THE FORWARD SCATTERING (FS), SIDE SCATTERING (SS), AND BACK SCATTERING (BS) REGIONS ARE SHADED BLUE, RED, AND GREEN RESPECTIVELY. THE SCATTERING ANGLE IS LIMITED TO 100° , BUT COMPLETE RESULTS FOUND IN APPX. 7.2.	67
FIGURE 3.19: DIFFERENCES IN THE ANGULAR LOCATIONS, IN COMPARISON TO THE MEASURED GLASS FIBRE DATA (ORANGE), FOUND FROM THE DIFFERENT MODELS USED. THE RIGHT SHOWS TO THE ORDER OF 13, THE LEFT 5. THE GENERALISED LORENTZ-MIE THEORY (GLMT) IS IN GREEN, THE AMSTERDAM DISCRETE DIPOLE APPROXIMATION (ADDA) IS IN BLUE, AND DIFFRACTION THEORY (DT) IS IN PURPLE.	68
FIGURE 4.1: ADDA GENERATED FORWARD SCATTERING EXAMPLES OF A $10\ \mu\text{M}$ LONG CYLINDER OF REFRACTIVE INDEX $1.5+0.5i$ WITH DIFFERENT DIAMETERS. THE CYLINDERS HAVE AN EULER ANGLE OF $(0, 90, 0)$, AND EACH IMAGE SHOWS THE SCATTERING ANGLE UP TO 90° OF THE FORWARD DIRECTION. THE GREEN ARROWS INDICATE THE MINIMUM.	72
FIGURE 4.2: GLMT GENERATED FORWARD SCATTERING EXAMPLES OF A $10\ \mu\text{M}$ LONG CYLINDER APPROXIMATION OF REFRACTIVE INDEX $1.5+0.5i$ AT DIFFERENT DIAMETER INPUTS. THE CYLINDERS HAVE AN EULER ANGLE OF $(0, 90, 0)$, AND EACH IMAGE SHOWS 90° OF THE FORWARD SCATTERING PATTERNS. THE GREEN ARROWS INDICATE THE MINIMUM.	73
FIGURE 4.3: CENTRAL VERTICAL COMPONENTS OF THE SCATTERING PATTERNS OF $10\ \mu\text{M}$ LONG CYLINDERS OF VARYING DIAMETERS, MODELLED IN ADDA.	73
FIGURE 4.4: MINIMUM LOCATIONS FOUND FROM BOTH GLMT (BLUE) AND ADDA (ORANGE) MODELLED DATA AGAINST THE INPUT DIAMETER. A COMPARISON OF THE THEORETICAL RESULTS FROM EQUATION 2.3 ARE ALSO INCLUDED AS A YELLOW DASHED LINE.	74
FIGURE 4.5: ADDA (TOP ROW) AND GLMT (BOTTOM ROW) GENERATED FORWARD SCATTERING RESULTS OF A CYLINDER OF DIAMETER $0.5\ \mu\text{M}$ AND REFRACTIVE INDEX $1.5+0.5i$ FOR A RANGE OF LENGTHS. THE CYLINDERS HAVE AN EULER ANGLE OF $(0, 90, 0)$, AND EACH IMAGE SHOWS 90° OF THE FORWARD SCATTERING PATTERNS.	75
FIGURE 4.6: CENTRAL HORIZONTAL COMPONENTS OF THE SCATTERING PATTERNS OF $10\ \mu\text{M}$ LONG CYLINDERS OF VARYING DIAMETERS, MODELLED IN ADDA.	75
FIGURE 4.7: FULL-WIDTH HALF-MAX MEASUREMENTS OF THE CENTRAL HORIZONTAL COMPONENTS OF BOTH GLMT (BLUE) AND ADDA (ORANGE) AGAINST THE INPUT LENGTH PARAMETERS. A COMPARISON OF THE THEORETICAL RESULTS FROM EQUATION 2.3 ARE ALSO INCLUDED AS A YELLOW DASHED LINE.	76
FIGURE 4.8: ADDA-MODELLED FORWARD SCATTERING EXAMPLES OF $10\ \mu\text{M}$ LONG CYLINDERS (TOP) FOR DIAMETERS OF $1\ \mu\text{M}$ (RIGHT) AND $0.5\ \mu\text{M}$ (LEFT) TO DEMONSTRATE THE PROMINENCE OF THE MINIMUM POINTS IN THEIR CENTRAL VERTICAL COMPONENTS (BOTTOM). THE REFRACTIVE INDEX OF THE CYLINDERS ARE $1.5 + 0.5i$.	77
FIGURE 4.9: FULL-WIDTH HALF MAXIMUM MEASUREMENTS OF THE CENTRAL HORIZONTAL COMPONENT OF THE FORWARD SCATTERING PATTERN OF A $10\ \mu\text{M}$ LONG CYLINDER MODELLED IN ADDA (LEFT) AT A RANGE OF DIAMETERS. RIGHT SHOWS THE MINIMUM MEASUREMENTS OF A $1\ \mu\text{M}$ DIAMETER CYLINDER, MODELLED IN ADDA WITH A RANGE OF DIFFERENT LENGTHS.	78
FIGURE 4.10: ADDA 90° FORWARD SCATTERING RESULTS OF A $0.5\ \mu\text{M}$ DIAMETER BY $10\ \mu\text{M}$ LONG CYLINDER OF REFRACTIVE INDEX $1.5+0.5i$ AT DIFFERENT A Euler Angles For $(\alpha, 90, 0)$.	79

FIGURE 4.11: ADDA 90° FORWARD SCATTERING RESULTS OF A 0.5 μM DIAMETER BY 10 μM LONG CYLINDER OF REFRACTIVE INDEX 1.5+0.5i AT DIFFERENT B EULER ANGLES FOR (0, B, 0).	79
FIGURE 4.12: COMPARISON OF CENTRAL VERTICAL COMPONENTS OF GLMT (BLUE) AND ADDA (ORANGE) OF A 0.5 μM DIAMETER BY 10 μM LONG CYLINDER AT DIFFERENT B EULER ANGLES.	80
FIGURE 4.13: EXAMPLES OF CYLINDER ORIENTATION USING EULER ANGLES. THE TWO LEFT IMAGES SHOW A CHANGE IN THE A ANGLE, WITH B AND Γ SET AT 90° AND 0° RESPECTIVELY, CORRESPONDING TO A ROTATION IN THE X – Y PLANE (MAGENTA). THE TWO RIGHT IMAGES SHOW A CHANGE IN THE B ANGLE, WITH A AND Γ BOTH SET AT 0°, CORRESPONDING TO A ROTATION IN THE Z – Y PLANE (GREEN).	80
FIGURE 4.14: RELATIONSHIP OF THE RADIUS OF CURVATURE FITTED TO THE RESULTING 90° FORWARD SCATTERING RESULTS OF ADDA FROM A 0.5 μM DIAMETER BY 10 μM LONG CYLINDER OF REFRACTIVE INDEX 1.5+0.5i FOR DIFFERENT B ANGLES (LEFT). RIGHT SHOWS AN EXAMPLE OF THE 90° FORWARD SCATTERING INCLUDING THE FITTED CIRCLE.	81
FIGURE 4.15: EXAMPLES OF THE CIRCLE FITTING FOR ORIENTATION MEASUREMENTS AT SMALL ANGLES TO EXPLAIN THE NON-MONOTONIC RESULTS OF FIGURE 4.14.	82
FIGURE 4.16: FULL-WIDTH HALF-MAXIMUM MEASUREMENTS OF THE CENTRAL HORIZONTAL COMPONENT (LEFT) AND THE MINIMUM OF THE CENTRAL VERTICAL COMPONENT (RIGHT) OF THE 90° FORWARD SCATTERING OF A 1 μM DIAMETER BY 10 μM LONG CYLINDER MODELLED IN ADDA.	82
FIGURE 4.17: RESULTS SHOWN IN FIGURE 4.16 BUT LIMITED TO B ANGLES BETWEEN 60° AND 90°.	83
FIGURE 4.18: ADDA (TOP ROW) AND GLMT (BOTTOM ROW) 90° FORWARD SCATTERING RESULTS OF 0.5 μM DIAMETER BY 10 μM LONG CYLINDERS OF DIFFERENT REAL REFRACTIVE INDEX.	84
FIGURE 4.19: ADDA (TOP ROW) AND GLMT (BOTTOM ROW) 90° FORWARD SCATTERING RESULTS OF 0.5 μM DIAMETER BY 10 μM LONG CYLINDERS OF DIFFERENT IMAGINARY REFRACTIVE INDEX.	84
FIGURE 4.20: FWHM (LEFT) AND MINIMUM (RIGHT) MEASUREMENTS FOUND FOR GLMT AND ADDA FROM THE 90° FORWARD SCATTERING FROM A 0.5 μM DIAMETER BY 10 μM LONG CYLINDER FOR DIFFERENT REAL REFRACTIVE INDICES.	85
FIGURE 4.21: FWHM (LEFT) AND MINIMUM (RIGHT) MEASUREMENTS FOUND FOR GLMT AND ADDA FROM THE 90° FORWARD SCATTERING FROM A 0.5 μM DIAMETER BY 10 μM LONG CYLINDER FOR DIFFERENT IMAGINARY REFRACTIVE INDICES.	85
FIGURE 4.22: RESULTS FOR THE MEASUREMENTS OF THE ANGULAR MINIMUM LOCATION (LEFT COLUMN) AND THE FWHM (RIGHT COLUMN) FOR BOTH ADDA- (TOP ROW) AND GLMT- (BOTTOM ROW) MODELLED DATA. THE GREEN BARS INDICATE A VARIATION IN IMAGINARY REFRACTIVE INDEX, WITH A FIXED REAL PART OF $1.5m = 1.5 + imi$, THE PURPLE BARS INDICATE A VARIATION IN REAL REFRACTIVE INDEX, WITH A FIXED IMAGINARY PART OF $0.5m = mr + i0.5$, AND THE RED BARS INDICATE A VARIATION IN REAL REFRACTIVE INDEX, WITH A FIXED IMAGINARY PART OF $0m = mr + i0.0$.	86
FIGURE 4.23: ADDA-MODELLED SCATTERING EXAMPLES FROM A 2.5 μM DIAMETER BY 10 μM LONG CYLINDER WITH REFRACTIVE INDICES OF 1.1+i0, 1.5+i0, AND 1.45+i0.5, SHOWN IN BLUE, ORANGE, AND YELLOW RESPECTIVELY.	87
FIGURE 4.24: A 3D MODEL OF A 0.75 μM DIAMETER CYLINDER OF A CHORD LENGTH OF 10 μM AND A RADIUS OF CURVATURE ~11.4 μM (LEFT) AND THE RESULTING 90° FORWARD SCATTERING (RIGHT). THE SCATTERING PATTERN WAS MODELLED IN ADDA FOR REFRACTIVE INDEX 1.5+0.5i AT AN EULER ANGLE OF (0, 90, 0).	88
FIGURE 4.25: DIAMETER REFERENCE DATA MEASUREMENT EXAMPLE. CYLINDERS OF A REFRACTIVE INDEX OF 1.5+0.5i, LENGTH 10 μM, AND AN EULER ANGLE OF (0, 90, 0) WERE USED TO GENERATE THE SCATTERING IMAGES USED TO GENERATE THE DATA. A MINIMUM IS FOUND AT 25°, INDICATING A DIAMETER OF 1.12 μM (GREEN ARROWS) WHEN USING EITHER THE GLMT OR ADDA REFERENCE DATA. RESULTS FROM COMPUTING THE SINGLE SLIT DIFFRACTION ARE INCLUDED FOR INTEREST.	89
FIGURE 4.26: THE GRADIENT OF A LINE OF BEST FIT BETWEEN THE SCATTERING ANGLES OF 6.75° AND 9.5° OF THE CENTRAL VERTICAL COMPONENT OF THE 26° FORWARD SCATTERING OF A 10 μM LONG CYLINDER MODELLED IN BOTH ADDA (ORANGE) AND GLMT (BLUE) FOR DIFFERENT DIAMETERS (LEFT). RIGHT SHOWS AN EXAMPLE OF THE SCATTERING AND THE WAY IN WHICH THE GRADIENT IS MEASURED ALONG WITH A YELLOW CIRCLE INDICATING THE MINIMUM.	91
FIGURE 4.27: 26° FORWARD SCATTERING OF A 1.52 μM DIAMETER BY ~10 μM LONG CYLINDER MODELLED IN ADDA (LEFT). THE GREEN VERTICAL SECTION AND THE MAGENTA HORIZONTAL SECTION REPRESENTS TWO LINEAR ARRAYS, THE AVERAGES OF THESE SECTIONS ARE SHOWN ON THE TOP RIGHT AND BOTTOM RIGHT RESPECTIVELY.	92
FIGURE 4.28: REFERENCE DATA CREATED USING ADDA MODEL (TOP) AND GLMT MODEL (BOTTOM) FOR THE MINIMUM DEPENDING ON DIAMETER (LEFT), GRADIENT OF THE SCATTERING DEPENDING ON DIAMETER (CENTRE), AND THE FWHM DEPENDING ON THE LENGTH (RIGHT).	93

FIGURE 4.29: DIAMETER MEASUREMENT RESULTS FROM ADDA MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). THE BLUE REPRESENTS THE MEASUREMENTS USING THE MINIMUM AND THE ORANGE REPRESENTS THE MEASUREMENTS USING THE GRADIENT. THE MEASUREMENTS (MEASURED DIAMETER) ARE PLOTTED AGAINST THE INPUT DIAMETER.	94
FIGURE 4.30: DIAMETER MEASUREMENT RESULTS FROM GLMT MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). THE BLUE REPRESENTS THE MEASUREMENTS USING THE FIRST ANGULAR MINIMUM LOCATIONS AND THE ORANGE REPRESENTS THE MEASUREMENTS USING THE GRADIENT. THE MEASUREMENTS (MEASURED DIAMETER) ARE PLOTTED AGAINST THE INPUT DIAMETER.	95
FIGURE 4.31: DIAMETER MEASUREMENT RESULTS FROM ADDA MODELLED DATA USING THE SECTION METHOD (TOP) AND THE TOTAL METHOD (BOTTOM). THE PLOTS ON THE LEFT-HAND SIDE SHOW THE DIAMETER RESULTS USING THE GRADIENT METHOD AND THE PLOTS ON THE RIGHT-HAND SIDE SHOW THE RESULTS OF THE MINIMUM METHOD. THE SCATTER POINTS ARE COLOUR-CODED TO THE IMAGINARY PART OF THE REFRACTIVE INDEX, SHOWN AS A COLOUR BAR ON THE RIGHT-HAND SIDE OF THE PLOTS.	96
FIGURE 4.32: DIAMETER MEASUREMENT RESULTS FROM GLMT MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). THE PLOTS ON THE LEFT-HAND SIDE SHOW THE DIAMETER RESULTS USING THE GRADIENT METHOD AND THE PLOTS ON THE RIGHT-HAND SIDE SHOW THE RESULTS OF THE MINIMUM METHOD. THE SCATTER POINTS ARE COLOUR-CODED TO THE IMAGINARY PART OF THE REFRACTIVE INDEX, SHOWN AS A COLOUR BAR ON THE RIGHT-HAND SIDE OF THE PLOTS.	96
FIGURE 4.33: LENGTH MEASUREMENT RESULTS FROM ADDA MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT).	97
FIGURE 4.34: LENGTH MEASUREMENT RESULTS FROM GLMT MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT).	98
FIGURE 4.35: COMPARISONS OF THE MEASURED AND REFERENCE DIAMETERS FROM THE ADDA-MODELLED DATA. TOP ROW SHOWS THE REFERENCE DATA (ORANGE) FOR THE GRADIENT MEASUREMENTS FOR BOTH THE TOTAL AND SECTION METHODS (LEFT AND RIGHT RESPECTIVELY). OVERLAYED (BLUE DOTS) ARE THE GRADIENT MEASUREMENTS PLOTTED AGAINST THE MEASURED DIAMETER. THE BOTTOM ROW SHOWS THE SAME RESULTS BUT FOR THE MINIMUM MEASUREMENTS.	99
FIGURE 4.36: COMPARISONS OF THE MEASURED AND REFERENCE LENGTHS FROM THE ADDA-MODELLED DATA. THE PLOTS SHOW THE REFERENCE DATA (ORANGE) FOR THE FWHM MEASUREMENTS FOR BOTH THE TOTAL AND SECTION METHODS (LEFT AND RIGHT RESPECTIVELY). OVERLAYED (BLUE DOTS) ARE THE FWHM MEASUREMENTS PLOTTED AGAINST THE MEASURED LENGTH.	99
FIGURE 4.37: R-SQUARED VALUES FOR THE GRADIENT DIAMETER MEASUREMENT RESULTS COMPARED TO A FUNCTION OF $y = x$ FOR DATA MODELLED IN ADDA. THE TOP SHOWS THE RESULTS USING THE SECTION METHOD, THE BOTTOM SHOWS THE RESULTS USING THE TOTAL METHOD. THE Y-AXIS INDICATES THE SMALLER ANGULAR LIMIT, CLOSER TO THE FORWARD SCATTERING DIRECTION, THE X-AXIS INDICATES THE LARGER ANGULAR LIMIT.	101
FIGURE 4.38: R-SQUARED VALUES FOR THE GRADIENT DIAMETER MEASUREMENT RESULTS COMPARED TO A FUNCTION OF $y = x$ FOR DATA MODELLED IN GLMT. THE TOP SHOWS THE RESULTS USING THE SECTION METHOD, THE BOTTOM SHOWS THE RESULTS USING THE TOTAL METHOD. THE Y-AXIS INDICATES THE SMALLER ANGULAR LIMIT, CLOSER TO THE FORWARD SCATTERING DIRECTION, THE X-AXIS INDICATES THE LARGER ANGULAR LIMIT.	102
FIGURE 4.39: HEATMAPS OF R-SQUARED VALUES FOUND FROM THE RESULTS OF THE LENGTH MEASUREMENTS (RIGHT) AND THE DIAMETER MEASUREMENTS (LEFT) FOR BOTH THE SECTION (TOP) AND TOTAL (BOTTOM) MEASUREMENT METHODS USING DIFFERENT REFRACTIVE INDICES.	103
FIGURE 4.40: HEATMAP OF THE MEAN R-SQUARED VALUE FOUND FOR BOTH DIAMETER AND LENGTH MEASUREMENT METHODS USING REFERENCE DATA OF DIFFERENT REFRACTIVE INDICES.	104
FIGURE 5.1: EXPERIMENTAL SET-UP.	107
FIGURE 5.2: DIAGRAM OF DRY AEROSOLISER DEVICE.	108
FIGURE 5.3: MICROGRAPHS OF THE SUPERWOOL PLUS SAMPLES TAKEN AT 100× MAGNIFICATION (LEFT) AND 500× MAGNIFICATION.	109
FIGURE 5.4: MICROGRAPHS OF THE SUPERWOOL HT SAMPLES TAKEN AT 100× MAGNIFICATION (LEFT) AND 500× MAGNIFICATION.	109
FIGURE 5.5: MICROGRAPHS OF THE BLANKET MT2 SAMPLES TAKEN AT 100× MAGNIFICATION (LEFT) AND 500× MAGNIFICATION.	109

FIGURE 5.6: MICROGRAPHS OF THE ALPHAWOOL HA SAMPLES TAKEN AT 100× MAGNIFICATION (LEFT) AND 500× MAGNIFICATION.	109
FIGURE 5.7: MICROGRAPH OF THE GYPSUM SAMPLE TAKEN AT 100× MAGNIFICATION (LEFT) AND 500× MAGNIFICATION.	110
FIGURE 5.8: MICROGRAPH OF THE WOLLASTONITE SAMPLE TAKEN AT 100× MAGNIFICATION (LEFT) AND 500× MAGNIFICATION.	110
FIGURE 5.9: MICROGRAPH OF THE CAFFEINE POWDER SAMPLE TAKEN AT 100× MAGNIFICATION (LEFT) AND 500× MAGNIFICATION.	110
FIGURE 5.10: MICROGRAPH OF THE KETTLE SCALE WHISKER SAMPLE TAKEN AT 100× MAGNIFICATION (LEFT) AND 500× MAGNIFICATION.	111
FIGURE 5.11: REFERENCE DATA MODELLED USING ADDA. THE MINIMUM DEPENDENCE ON DIAMETER IS SHOWN IN THE LEFT-HAND SIDE, THE GRADIENT OF THE LINE OF BEST FIT MEASURED BETWEEN THE SCATTERING ANGLES OF 7.25° AND 9° DEPENDENCE ON DIAMETER IS SHOWN IN THE CENTRE, AND THE FWHM MEASUREMENT DEPENDENCE ON THE LENGTH IS SHOWN IN THE RIGHT-HAND SIDE. EACH MEASUREMENT WAS TAKEN USING A CYLINDER OF REFRACTIVE INDEX 1.8+0.8i USING BOTH THE TOTAL (BLUE) AND SECTION (ORANGE) METHODS, MORE INFORMATION CAN BE FOUND IN CHAPTER 4.	112
FIGURE 5.12: PARTICLE PHASE DISCRIMINATOR MK. 2 (PPD2) INNER WORKINGS DIAGRAM.	113
FIGURE 5.13: PPD2 SCATTERING DATA OF A REFRACTORY CERAMIC FIBRE.	114
FIGURE 5.14: FWHM MEASUREMENTS OF A 0.5 μM DIAMETER BY 10 μM LONG ADDA-MODELLED CYLINDER, USING BOTH THE TOTAL AND SECTION TECHNIQUES. LEFT SHOWS THE FWHM DEPENDENCE ON B EULER ANGLES FOR (0, B, 0) AND RIGHT SHOWS THE FWHM DEPENDENCE ON A EULER ANGLES FOR (A, 90, 0).	115
FIGURE 5.15: FWHM MEASUREMENTS OF A 0.5 μM DIAMETER BY 10 μM LONG ADDA-MODELLED CYLINDER, CHANGING BOTH THE B EULER ANGLE FOR (0, B, 0) (LEFT) AND A EULER ANGLE FOR (A, 90, 0) (RIGHT), MEASURED USING THE SECTION TECHNIQUE OF VARYING ANGULAR LIMITS. THE TOP SHOWS THE FULL ORIENTATIONAL RANGE 0° – 90° AND THE BOTTOM HIGHLIGHTS 60° – 90°.	116
FIGURE 5.16: PPD2 SCATTERING DATA (BLUE) USED FOR LENGTH MEASUREMENT AS AN EXAMPLE OF IMAGE SATURATION, SHOWING A 2.24° ANGLE OF SATURATED DATA HIGHLIGHTED IN PINK.	117
FIGURE 5.17: PPD2 SCATTERING DATA ANALYSIS EXAMPLE. THE IMAGE ON THE LEFT SHOWS AN EXAMPLE OF LIGHT SCATTERED FROM A FIBRE, THE GREEN SECTION IS USED FOR THE DIAMETER MEASUREMENT (BOTTOM RIGHT), AND THE MAGENTA SECTIONS ARE FOR THE LENGTH MEASUREMENT (TOP RIGHT).	118
FIGURE 5.18: REFERENCE DATA MODELLED USING ADDA. THE MINIMUM DEPENDENCE ON DIAMETER IS SHOWN IN THE LEFT-HAND SIDE PLOTS, THE GRADIENT OF THE LINE OF BEST FIT MEASURED BETWEEN THE SCATTERING ANGLES OF 7.25° AND 9° DEPENDENCE ON DIAMETER IS SHOWN UNDER GRADIENT/DIAMETER, THE FWHM MEASUREMENT DEPENDENCE ON THE LENGTH IS SHOWN UNDER FWHM/LENGTH, AND THE NEW ALTERNATIVE LENGTH MEASUREMENT IS SHOWN ON THE FAR RIGHT. EACH MEASUREMENT WAS TAKEN USING A CYLINDER OF REFRACTIVE INDEX 1.8+0.8i USING BOTH THE TOTAL (BLUE) AND SECTION (ORANGE) METHODS, MORE INFORMATION CAN BE FOUND IN CHAPTER 4.	119
FIGURE 5.19: SECTION OF MICROGRAPH FROM ONE OF THE REFRACTORY CERAMIC FIBRE SAMPLES.	119
FIGURE 5.20: SCATTERING EXAMPLE TO ILLUSTRATE THE POSSIBLE ERRORS FOUND FOR THE GRADIENT MEASUREMENTS WHERE THE BOTTOM RIGHT IMAGE IS THE SCATTERED LIGHT, THE TOP RIGHT PLOT IS THE DATA USED FOR THE DIAMETER MEASUREMENT FROM THE SECTION METHOD, AND THE LEFT PLOT IS AN ENLARGEMENT OF THE GREEN RECTANGLE. THE YELLOW LINE SHOWS THE FITTED LINE FOR THE GRADIENT MEASUREMENT, THE ORANGE LINE IS THE SMOOTHED DATA, THE RED LINES INDICATE THE MINIMUM LOCATIONS, AND THE BLUE LINE IS THE ORIGINAL DATA.	121
FIGURE 5.21: SCATTERING EXAMPLE TO ILLUSTRATE THE POSSIBLE ERRORS FOUND FOR THE MINIMUM MEASUREMENTS WHERE THE BOTTOM RIGHT IMAGE IS THE SCATTERED LIGHT, THE TOP RIGHT PLOT IS THE DATA USED FOR THE DIAMETER MEASUREMENT FROM THE SECTION METHOD, AND THE LEFT PLOT IS AN ENLARGEMENT OF THE GREEN RECTANGLE. THE ORANGE LINE IS THE SMOOTHED DATA, THE RED LINES INDICATE THE MINIMUM LOCATIONS, AND THE BLUE LINE IS THE ORIGINAL DATA.	122
FIGURE 5.22: SCATTERING EXAMPLE TO ILLUSTRATE THE POSSIBLE ERRORS FOUND FOR THE FWHM MEASUREMENTS WHERE THE BOTTOM RIGHT IMAGE IS THE SCATTERED LIGHT, THE TOP RIGHT PLOT IS THE DATA USED FOR THE LENGTH MEASUREMENT FROM THE SECTION METHOD, AND THE LEFT PLOT IS AN ENLARGEMENT OF THE MAGENTA RECTANGLE. THE LIGHT MAGENTA LINES INDICATE THE HALF-WIDTH (HORIZONTAL) AND THE EDGES OF THE CURVE AT THE HALF-WIDTH (VERTICAL), THE RED LINES INDICATE THE MINIMUM LOCATIONS, AND THE BLUE LINE IS THE ORIGINAL DATA.	123

FIGURE 5.23: SCATTERING EXAMPLE TO ILLUSTRATE THE POSSIBLE ERRORS FOUND FOR THE MINIMUM MEASUREMENTS WHERE THE BOTTOM RIGHT IMAGE IS THE SCATTERED LIGHT, THE TOP RIGHT PLOT IS THE DATA USED FOR THE LENGTH MEASUREMENT FROM THE SECTION METHOD, AND THE LEFT PLOT IS AN ENLARGEMENT OF THE MAGENTA RECTANGLE. THE ORANGE LINE IS THE SMOOTHED DATA, THE RED LINES INDICATE THE MINIMUM LOCATIONS, AND THE BLUE LINE IS THE ORIGINAL DATA. _____	124
FIGURE 5.24: DIAMETER MEASUREMENT RESULTS USING THE TOTAL (BLUE) AND SECTION (PURPLE) TECHNIQUES FOR THE SIX SELECTED FIBRE SAMPLES, MEASURED USING ADDA-MODELLED REFERENCE DATA. THE MEDIAN DIAMETER IS INCLUDED IN THE LEGEND. _____	125
FIGURE 5.25: LENGTH MEASUREMENT RESULTS USING THE TOTAL (BLUE) AND SECTION (PURPLE) TECHNIQUES FOR THE SIX SELECTED FIBRE SAMPLES, MEASURED USING ADDA-MODELLED REFERENCE DATA. THE MEDIAN LENGTH IS INCLUDED IN THE LEGEND. _____	126
FIGURE 5.26: LENGTH MEASUREMENT RESULTS USING THE TOTAL (BLUE) AND SECTION (PURPLE) TECHNIQUES FOR THE SIX SELECTED FIBRE SAMPLES, MEASURED USING ADDA-MODELLED REFERENCE DATA AND USING THE ALTERNATIVE MINIMUM MEASUREMENTS. THE MEDIAN LENGTH IS INCLUDED IN THE LEGEND. _____	127
FIGURE 5.27: MEASUREMENT RESULTS USING THE TOTAL (BLUE) AND SECTION (PURPLE) TECHNIQUES OF THE COMBINED SAMPLES, MEASURED USING ADDA-MODELLED REFERENCE DATA. LEFT SHOWS THE DIAMETER DISTRIBUTIONS, MIDDLE SHOWS THE LENGTHS MEASURED USING THE FWHM-DOMINATED SYSTEM, AND RIGHT SHOWS THE LENGTHS MEASURED USING THE MINIMUM. THE MEDIAN SIZE IS INCLUDED IN EACH LEGEND. _____	127
FIGURE 5.28: PPD2 SCATTERING IMAGES OF AN AGGLOMERATE FIBRE, A CURVED FIBRE, AMORPHOUS DUST, A FIBRE AT AN OBLIQUE ANGLE OF ORIENTATION, AND THE CAMERA TRIGGERING ON ELECTRICAL NOISE (FROM LEFT TO RIGHT). ____	128
FIGURE 5.29: EXAMPLES OF LIGHT SCATTERING IMAGES FROM DIFFERENT SAMPLES REJECTED BY THE MEASUREMENT SYSTEM USING THE TOTAL TECHNIQUE AND THE ADDA-MODELLED REFERENCE DATA. _____	129
FIGURE 5.30: MICROGRAPH RESULTS SHOWING THE PROBABILITY DISTRIBUTIONS OF THE MEASURED DIAMETERS OF THE COLLECTED FIBRE SAMPLES. _____	130
FIGURE 5.31: MICROGRAPH RESULTS SHOWING THE PROBABILITY DISTRIBUTIONS OF THE MEASURED LENGTHS OF THE COLLECTED FIBRE SAMPLES. _____	130
FIGURE 5.32: MICROGRAPH RESULTS SHOWING THE PROBABILITY DISTRIBUTIONS OF THE MEASURED DIAMETERS (LEFT) AND LENGTHS (RIGHT) OF THE COMBINED COLLECTED FIBRE SAMPLES. _____	131
FIGURE 5.33: MICROGRAPH SECTION EXAMPLE OF TEST DUST SAMPLE DURING CLEARING ATTEMPT. _____	132
FIGURE 5.34: COMPARISONS OF THE DIAMETER SIZE PROBABILITY DISTRIBUTIONS OF THE MICROGRAPH DATA (DASHED ORANGE LINE) AND THE DIAMETER MEASUREMENTS OF THE SCATTERING DATA USING THE SECTION TECHNIQUE AND THE ADDA-MODELLED REFERENCE DATA. THE MEDIAN DIAMETER IS INCLUDED IN THE LEGEND. _____	132
FIGURE 5.35: COMPARISONS OF THE LENGTH SIZE PROBABILITY DISTRIBUTIONS OF THE MICROGRAPH DATA (DASHED ORANGE LINE) AND THE LENGTH MEASUREMENTS OF THE SCATTERING DATA USING THE SECTION METHOD (RIGHT) AND THE TOTAL METHOD (LEFT). THE MEDIAN LENGTH IS INCLUDED IN EACH LEGEND. _____	133
FIGURE 5.36: COMPARISONS OF THE LENGTH SIZE PROBABILITY DISTRIBUTIONS OF THE MICROGRAPH DATA (DASHED ORANGE LINE) AND THE LENGTH MEASUREMENTS OF THE SCATTERING DATA USING THE SECTION METHOD (RIGHT) AND THE TOTAL METHOD (LEFT), MADE USING MINIMUM MEASUREMENTS. THE MEDIAN LENGTH IS INCLUDED IN EACH LEGEND. _____	133
FIGURE 5.37: COMPARISONS OF THE DIAMETER SIZE PROBABILITY DISTRIBUTIONS OF THE MICROGRAPH DATA (DASHED ORANGE LINE) AND THE DIAMETER MEASUREMENTS OF THE SCATTERING DATA USING THE SECTION METHOD (RIGHT) AND THE TOTAL METHOD (LEFT) FOR DIAMETERS < 1.62 μm . THE MEDIAN DIAMETER IS INCLUDED IN EACH LEGEND. _____	134
FIGURE 5.38: COMPARISONS OF THE DIAMETER SIZE PROBABILITY DISTRIBUTIONS OF THE MICROGRAPH DATA (DASHED ORANGE LINE) AND THE DIAMETER MEASUREMENTS OF THE SCATTERING DATA USING THE SECTION METHOD (RIGHT) AND THE TOTAL METHOD (LEFT) FOR DIAMETERS $\geq 1.62 \mu\text{m}$. THE MEDIAN DIAMETER IS INCLUDED IN EACH LEGEND. _____	134
FIGURE 5.39: SCATTERING IMAGE EXAMPLES FROM DIFFERENT DIAMETER RANGES FOR THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). _____	135
FIGURE 5.40: SCATTERING IMAGE EXAMPLES FROM DIFFERENT LENGTH RANGES MEASURED USING THE FWHM FOR THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). _____	136
FIGURE 5.41: SCATTERING IMAGE EXAMPLES FROM DIFFERENT LENGTH RANGES MEASURED USING THE MINIMUM FOR THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). NO DATA WAS FOUND FOR 0 μm – 2 μm LENGTHS OF THE TOTAL METHOD. _____	136

FIGURE 5.42: PPD2 SCATTERING DATA (TOP ROW) SHOWING THE FORWARD SCATTERING IMAGE WITH MARKED SECTIONS (LEFT), THE SCATTERING DATA USED FOR THE DIAMETER MEASUREMENTS (MIDDLE), AND THE SCATTERING DATA USED FOR THE LENGTH MEASUREMENTS (RIGHT). THE RED VERTICAL LINES INDICATE THE MINIMUM. THE BOTTOM ROW SHOWS THE SAME ANALYSIS OF THE SCATTERING MODELLED BY ADDA OF A $1.8\text{ }\mu\text{m}$ DIAMETER BY $11\text{ }\mu\text{m}$ LONG CYLINDER THAT WERE THE DIMENSIONS OBTAINED FROM THE TOP ROW. _____	138
FIGURE 5.43: COMPARISONS OF THE LENGTH SIZE PROBABILITY DISTRIBUTIONS OF THE MICROGRAPH DATA (DASHED ORANGE LINE) AND THE LENGTH MEASUREMENTS OF THE SCATTERING DATA USING THE SECTION METHOD (RIGHT) AND THE TOTAL METHOD (LEFT), MADE USING MINIMUM MEASUREMENTS AFTER FURTHER OPTIMISATION. THE MEDIAN LENGTH IS INCLUDED IN EACH LEGEND. _____	139
FIGURE 5.44: COMPARISONS OF THE LENGTH SIZE PROBABILITY DISTRIBUTIONS OF THE MICROGRAPH DATA (DASHED ORANGE LINE) AND THE LENGTH MEASUREMENTS OF THE SCATTERING DATA USING THE SECTION METHOD (RIGHT) AND THE TOTAL METHOD (LEFT), MADE USING FWHM MEASUREMENTS AFTER FURTHER OPTIMISATION. THE MEDIAN LENGTH IS INCLUDED IN EACH LEGEND. _____	139
FIGURE 5.45: COMPARISONS OF THE DIAMETER SIZE PROBABILITY DISTRIBUTIONS OF THE MICROGRAPH DATA (DASHED ORANGE LINE) AND THE DIAMETER MEASUREMENTS OF THE SCATTERING DATA USING THE SECTION TECHNIQUE AND THE ADDA-MODELLED REFERENCE DATA WITH OPTIMISED BIN WIDTHS. THE MEDIAN DIAMETER IS INCLUDED IN THE LEGEND. _____	140
FIGURE 5.46: SCATTERING IMAGE EXAMPLES FROM DIFFERENT LENGTH RANGES MEASURED USING THE MINIMUM FOR THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). NO DATA WAS FOUND FOR THE $0\text{ }\mu\text{m} - 2\text{ }\mu\text{m}$ CATEGORY AND ONLY ONE EXAMPLE EACH FOR THE $2\text{ }\mu\text{m} - 4\text{ }\mu\text{m}$ CATEGORY. _____	140
FIGURE 5.47: CUMULATIVE DISTRIBUTION FUNCTIONS OF THE DIAMETER (LEFT) AND LENGTH (RIGHT) RESULTS FOR THE TOTAL (PURPLE) AND SECTION (ORANGE) MEASURED SCATTERING DATA, ALONGSIDE THE MICROGRAPH (BLUE) CUMULATIVE DISTRIBUTION FUNCTIONS. _____	141
FIGURE 6.1: SCATTERING EXAMPLES FROM GYPSUM FIBRES, CAPTURED USING PPD2, CATEGORISED INTO DIFFERENT PEAK TO MEAN (P2M) VALUES. THE COLUMNS SHOW THE ROTATIONAL MEAN P2M, THE SECTIONAL MEAN P2M, AND A COMBINATION FROM LEFT TO RIGHT RESPECTIVELY. _____	150
FIGURE 7.1: EXAMPLES (LEFT) OF TWO DIFFERENT WAVEFORMS (DASHED LINES) AND THEIR COMBINED WAVE (SOLID BLUE) AND THEIR CORRESPONDING FOURIER TRANSFORMS (RIGHT) SHOWING THE ABSOLUTE VALUE FOR EACH WAVEFORM AS DISCRETE BARS. _____	163
FIGURE 7.2: EXAMPLES OF TWO DIFFERENT WAVES OF DIFFERENT SPATIAL FREQUENCIES. THE LEFT SHOWS A SINGLE OSCILLATION OVER A DISTANCE L , HAVING A SPATIAL FREQUENCY OF 1. THE RIGHT SHOWS FIVE OSCILLATIONS OVER A DISTANCE L , HAVING A SPATIAL FREQUENCY OF 5. _____	164
FIGURE 7.3: DEMONSTRATION OF THE APPROXIMATION OF A SQUARE PULSE USING THE COMBINATION OF COSINE FUNCTIONS (RIGHT COLUMN) WITH INCREASING ORDERS FROM TOP TO BOTTOM. THE MIDDLE AND LEFT SHOW THE CORRESPONDING FOURIER TRANSFORMS AND ABSOLUTE VALUES THEREOF RESPECTIVELY. _____	165
FIGURE 7.4: SCATTERING RESULTS OF CARBON FIBRE SCATTERING EXPERIMENT COMPARED WITH RESULTS OF MODELS PLOTTED ON A LOGARITHMIC SCALE FOR THE POWER AGAINST THE SCATTERING ANGLE. THE FORWARD SCATTERING (FS), SIDE SCATTERING (SS), AND BACK SCATTERING (BS) REGIONS ARE SHADED BLUE, RED, AND GREEN RESPECTIVELY _____	166
FIGURE 7.5: SCATTERING RESULTS OF GLASS FIBRE SCATTERING EXPERIMENT COMPARED WITH RESULTS OF MODELS PLOTTED ON A LOGARITHMIC SCALE FOR THE POWER AGAINST THE SCATTERING ANGLE. THE FORWARD SCATTERING (FS), SIDE SCATTERING (SS), AND BACK SCATTERING (BS) REGIONS ARE SHADED BLUE, RED, AND GREEN RESPECTIVELY. ____	166
FIGURE 7.6: DIAMETER MEASUREMENT RESULTS FROM ADDA MODELLED DATA USING THE SECTION METHOD (TOP) AND THE TOTAL METHOD (BOTTOM). THE PLOTS ON THE LEFT-HAND SIDE SHOW THE DIAMETER RESULTS USING THE GRADIENT METHOD AND THE PLOTS ON THE RIGHT-HAND SIDE SHOW THE RESULTS OF THE MINIMUM METHOD. THE SCATTER POINTS ARE COLOUR-CODED TO THE REAL PART OF THE REFRACTIVE INDEX, SHOWN AS A COLOUR BAR ON THE RIGHT-HAND SIDE OF THE PLOTS. _____	167
FIGURE 7.7: DIAMETER MEASUREMENT RESULTS FROM GLMT MODELLED DATA USING THE SECTION METHOD (TOP) AND THE TOTAL METHOD (BOTTOM). THE PLOTS ON THE LEFT-HAND SIDE SHOW THE DIAMETER RESULTS USING THE GRADIENT METHOD AND THE PLOTS ON THE RIGHT-HAND SIDE SHOW THE RESULTS OF THE MINIMUM METHOD. THE SCATTER POINTS ARE COLOUR-CODED TO THE REAL PART OF THE REFRACTIVE INDEX, SHOWN AS A COLOUR BAR ON THE RIGHT-HAND SIDE OF THE PLOTS. _____	167

FIGURE 7.8: LENGTH MEASUREMENT RESULTS FROM ADDA MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). THE PLOTS ON THE TOP SHOW THE LENGTH RESULTS COLOUR-CODED USING THE IMAGINARY PART OF THE REFRACTIVE INDEX AND THE PLOTS ON THE BOTTOM SHOW THE RESULTS COLOUR-CODED USING THE REAL PART OF THE REFRACTIVE INDEX.	168
FIGURE 7.9: LENGTH MEASUREMENT RESULTS FROM GLMT MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). THE PLOTS ON THE TOP SHOW THE LENGTH RESULTS COLOUR-CODED USING THE IMAGINARY PART OF THE REFRACTIVE INDEX AND THE PLOTS ON THE BOTTOM SHOW THE RESULTS COLOUR-CODED USING THE REAL PART OF THE REFRACTIVE INDEX.	168
FIGURE 7.10: LENGTH MEASUREMENT RESULTS FROM ADDA MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). THE RESULTS ARE COLOUR-CODED USING INPUT DIAMETER.	169
FIGURE 7.11: LENGTH MEASUREMENT RESULTS FROM GLMT MODELLED DATA USING THE SECTION METHOD (LEFT) AND THE TOTAL METHOD (RIGHT). THE RESULTS ARE COLOUR-CODED USING INPUT DIAMETER.	169
FIGURE 7.12: COMPARISONS OF THE MEASURED AND REFERENCE DIAMETERS FROM THE GLMT-MODELLED DATA. TOP ROW SHOWS THE REFERENCE DATA (ORANGE) FOR THE GRADIENT MEASUREMENTS FOR BOTH THE TOTAL AND SECTION METHODS (LEFT AND RIGHT RESPECTIVELY). OVERLAYED (BLUE DOTS) ARE THE GRADIENT MEASUREMENTS PLOTTED AGAINST THE MEASURED DIAMETER. THE BOTTOM ROW SHOWS THE SAME RESULTS BUT FOR THE MINIMUM MEASUREMENTS.	170
FIGURE 7.13: ADDA MODELLED DATA EXAMPLE OF THE MUELLER MATRIX OUTPUT, ORGANISED INTO A θ BY ϕ GRID (LEFT) AND TRANSFORMED INTO THE FORWARD 26° SCATTERING (RIGHT).	171
FIGURE 7.14: PPD2 EXAMPLE DATA BEFORE (LEFT) AND AFTER (RIGHT) CROPPING INTO A SQUARE IMAGE.	172
FIGURE 7.15: SEGMENTATION EXAMPLE OF SCATTERING FROM A FIBRE, CAPTURED BY PPD2 (LEFT) AND THE PIXEL SUM OF EACH SEGMENT DEPENDING ON ROTATIONAL ANGLE (RIGHT). NOTE: THE ANGLE MARKINGS ON THE SCATTERING IMAGE (LEFT) USE THE INSIDE MEASUREMENTS SHOWN FOR THE RADIAL SUM (RIGHT).	173
FIGURE 7.16: EXAMPLES OF FORWARD SCATTERING PATTERNS FROM CURVED FIBRES, CAPTURED BY PPD2.	174
FIGURE 7.17: R-SQUARED VALUES FOR THE GRADIENT DIAMETER MEASUREMENT RESULTS COMPARED TO A FUNCTION OF $y = x$ FOR DATA MODELLED IN ADDA. THE TOP SHOWS THE RESULTS USING THE SECTION METHOD, THE BOTTOM SHOWS THE RESULTS USING THE TOTAL METHOD. THE Y-AXIS INDICATES THE SMALLER ANGULAR LIMIT, CLOSER TO THE FORWARD SCATTERING DIRECTION, THE X-AXIS INDICATES THE LARGER ANGULAR LIMIT.	175
FIGURE 7.18: R-SQUARED VALUES FOR THE GRADIENT DIAMETER MEASUREMENT RESULTS COMPARED TO A FUNCTION OF $y = x$ FOR DATA MODELLED IN GLMT. THE TOP SHOWS THE RESULTS USING THE SECTION METHOD, THE BOTTOM SHOWS THE RESULTS USING THE TOTAL METHOD. THE Y-AXIS INDICATES THE SMALLER ANGULAR LIMIT, CLOSER TO THE FORWARD SCATTERING DIRECTION, THE X-AXIS INDICATES THE LARGER ANGULAR LIMIT.	176
FIGURE 7.19: PPD2 SCATTERING DATA (TOP ROW) SHOWING THE FORWARD SCATTERING IMAGE WITH MARKED SECTIONS (LEFT), THE SCATTERING DATA USED FOR THE DIAMETER MEASUREMENTS (MIDDLE), AND THE SCATTERING DATA USED FOR THE LENGTH MEASUREMENTS (RIGHT). THE RED VERTICAL LINES INDICATE THE MINIMUM. THE BOTTOM ROW SHOWS THE SAME ANALYSIS OF THE SCATTERING MODELLED BY ADDA OF A $0.7 \mu\text{m}$ DIAMETER BY $3.5 \mu\text{m}$ LONG CYLINDER THAT WERE THE DIMENSIONS OBTAINED FROM THE TOP ROW.	177
FIGURE 7.20: PPD2 SCATTERING DATA (TOP ROW) SHOWING THE FORWARD SCATTERING IMAGE WITH MARKED SECTIONS (LEFT), THE SCATTERING DATA USED FOR THE DIAMETER MEASUREMENTS (MIDDLE), AND THE SCATTERING DATA USED FOR THE LENGTH MEASUREMENTS (RIGHT). THE RED VERTICAL LINES INDICATE THE MINIMUM. THE BOTTOM ROW SHOWS THE SAME ANALYSIS OF THE SCATTERING MODELLED BY ADDA OF A $1.8 \mu\text{m}$ DIAMETER BY $11 \mu\text{m}$ LONG CYLINDER THAT WERE THE DIMENSIONS OBTAINED FROM THE TOP ROW.	177
FIGURE 7.21: PPD2 SCATTERING DATA (TOP ROW) SHOWING THE FORWARD SCATTERING IMAGE WITH MARKED SECTIONS (LEFT), THE SCATTERING DATA USED FOR THE DIAMETER MEASUREMENTS (MIDDLE), AND THE SCATTERING DATA USED FOR THE LENGTH MEASUREMENTS (RIGHT). THE RED VERTICAL LINES INDICATE THE MINIMUM. THE BOTTOM ROW SHOWS THE SAME ANALYSIS OF THE SCATTERING MODELLED BY ADDA OF A $0.75 \mu\text{m}$ DIAMETER BY $10 \mu\text{m}$ LONG CYLINDER THAT WERE THE DIMENSIONS OBTAINED FROM THE TOP ROW.	178

List of Tables

TABLE 1.1: SUMMARY OF VARIOUS OPCs, INCLUDING PARTICLE SIZE RANGE AND PHYSICAL DIMENSIONS. _____	10
TABLE 5.1: MANN-WHITNEY U TEST RESULTS SUMMARY FOR BOTH DIAMETER AND LENGTH MEASUREMENTS USING BOTH THE SECTION AND TOTAL METHODS COMPARED WITH THE MICROGRAPH SIZE DISTRIBUTIONS. _____	141
TABLE 5.2: TWO-SAMPLE KOLMOGOROV-SMIRNOV TEST RESULTS SUMMARY FOR BOTH DIAMETER AND LENGTH CUMULATIVE DISTRIBUTION FUNCTIONS USING BOTH THE SECTION AND TOTAL METHODS COMPARED WITH THE MICROGRAPH CUMULATIVE DISTRIBUTION FUNCTION. _____	142

Abbreviations

ACM	-	A sbestos C ontaining M aterials
ADDA	-	A msterdam D iscrete D ipole A pproximation
AES	-	A lkali E arth S ilicate
AFRICA	-	A sbestos F ibre R egular I nformal C ounting A rrangement
AIITS	-	A erosol I ce I nterface T ransmission S pectrometer
AIR PT	-	A ir and S tack E missions P roficiency T esting S cheme
APS	-	A erodynamic P article S izer
BG	-	B acillus G lobuli
BS	-	B ack S cattering
CAD	-	C omputer A ided D esign
CCD	-	C harge C oupled D evice
CNT	-	C arbon N ano T ube
CPC	-	C ondensation P article C ounter
CPS	-	C ondensation P article S izer
CW	-	C ontinuous W ave
DDA	-	D iscrete D ipole A pproximation
DMA	-	D ifferential M obility A nalysers
DT	-	D iffraction T heory
EDX	-	E nergy D ispersive X -ray (Spectroscopy)
ERM	-	E uropean R eference M ethod
FAM	-	F ibrous A erosol M onitor
FTIR	-	F ourier T ransform I nfared (Spectroscopy)
FS	-	F orward S cattering
FWHM	-	F ull W idth H alf M aximum
GLMT	-	G eneralised L orenz- M ie T heory
GO	-	G eometric O ptics
HEPA	-	H igh E fficiency P articulate A ir
HSE	-	H ealth and S afety E xecutive
INSST	-	I nstituto N acional de S eguridad y S alud en el T rabajo
LDPE	-	L ow D ensity P olyethylene
LED	-	L ight E mitting D iode
MBS	-	M ultiparameter B io-aerosol S ensor
MCE	-	M icro C ellulose E ster
MMMF	-	M an- M ade M ineral F ibres
MMVF	-	M an- M ade V itreous F ibres
MWCNT	-	M ulti W alled C arbon N ano T ube
NADH	-	N icotinamide A denine D inucleotide + H ydrogen
NIOSH	-	N ational I nstitute of O ccupational S afety and H ealth
OPC	-	O ptical P article C ounter
OPS	-	O ptical P article S izer
PBT	-	P arent B eam T racer
PCOM	-	P hase C ontract O ptical M icroscopy
PICC-FA	-	P rograma I nterlaboratorios de C ontrol de C alidad de F ibras de A mianto
PM	-	P articulate M atter
PMT	-	P hoto M ultiplier T ube
PPD	-	P article P hase D iscriminator

PSL	-	P olystyrene L atex
RCF	-	R efractory C eramic F ibres
RCS	-	R espirable C rystalline S ilica
RH	-	R elative H umidity
RNS	-	R eactive N itrogen S pecies
ROS	-	R eactive O xygen S pecies
RTDF	-	R ay T racing with D iffraction on F acets
SEM	-	S canning E lectron M icroscopy
SIBS	-	S pectral I ntensity B io-aerosol S ensor
SID	-	S mall I ce D etector
SS	-	S ide S cattering
SScaTT	-	S uperellipsoid S cattering T ool
SVF	-	S ynthetic V itreous F ibres
SWCNT	-	S ingle W alled C arbon N ano T ube
TEM	-	T ransmission E lectron M icroscopy
TNF-α	-	T umour N ecrosis F actor A lpha
ToF	-	T ime o f F light
UCASS	-	U niversal C loud and A erosol S ounding S ystem
UHHPC	-	U niversity of H ertfordshire's H igh- P erformance C omputing
UK	-	U nited K ingdom
US	-	U nited S tates
UV APS	-	U ltra- V iolet A erosol P article S izer
WASP	-	W orkplace A nalysis S cheme for P roficiency
WHO	-	W orld H ealth O rganisation
WIBS	-	W ide I ssue B io-aerosol S ensor

1 Introduction

*“When thou shalt stand before her gracious beam,
Whose bright eye all surveys, she of thy life
The future tenour will to thee unfold”.
-Dante Alighieri, The Divine Comedy, 1308*

1.1 A Quick History

It has been suggested that the use of asbestos started around 5000 years ago in Cyprus to make clothing, lamp wicks, and other domestic items (Ross & Nolan, 2003) and that there was no evidence into its potential adverse health effects in ancient times (Murray, 1990). Asbestos was also used by medieval alchemists who claimed the mineral grew as hairs from fire-resistant salamanders (Alleman & Mossman, 1997). The true source is, unfortunately, much less fantastic; mined from ophiolite terrain, oceanic plates that have mounted onto continental plates via tectonic movements. Asbestos is really a name for a group of crystalline mineral silicates that cover serpentine, which includes chrysotile asbestos, and amphibole, the more dangerous group that includes amosite asbestos (Sen, 2015).

The reason for its use was due to the incredible physical properties it possesses; a great heat insulator and fireproof, resistant to chemical and biological corrosion, mechanically strong, and can be woven into fabric. The amazing properties of this mineral was the reason behind its popularity and prolific use until around the end of World War II, where more evidence was given in its link with diseases. This eventually led to a ban in the UK in 1985 for amosite and crocidolite and 1999 for chrysotile (Sen, 2015). Fortunately, the physiological effects are now better understood, and its use has been banned in many countries and so it is no longer used to reinforce concrete or added to toothpaste. However, replacements for this material are still mostly of a fibrous nature and the toxicological effects of lung deposition are less understood but show similarities, as will be discussed in Section 1.2.1. As asbestos and fibrous replacements are still either present or currently used, prevention or reduction of exposure is necessary. The aim of this research is to investigate a means of detection of single airborne respirable fibres through light scattering techniques.

1.2 Health

1.2.1 Effects of Respirable Fibres

1.2.1.1 Macro-Effects

Very early documented cases of the effect of respirable asbestos, deposited within the human lung, demonstrate that the potential consequences of exposure have been known for at least 100 years. As an example, Cooke (1924), details an autopsy of a woman who worked in an asbestos mine for 20 years, dying at the age of 33. Fibre length distributions ranged from 3 μm to 400 μm and further descriptions gave several examples of extensive fibrosis, cavities, scar tissue, caseations, and “calcareous glands”. Extensive research has been carried out on the health effects of respirable asbestos following these early investigations, which include toxicity of different asbestos types (Mirata et al., 2022), different types of rodent studies (Madl & O’Neill, 2022), and developments in technology for inhalation studies (Wang et al., 2023a, 2023b). A list of potential diseases have been presented by Sen (2015): benign pleural plaques, thickening, and effusion; malignant mesothelioma and lung cancer. Asbestos has also been found in

abdominal areas, suggesting the possibility that the migration of the fibres within the body can cause disease in other areas – for example retroperitoneal fibrosis (Uibu et al., 2004).

1.2.1.2 Micro-Effects

The bio-mechanisms involved in the development of these diseases has also been thoroughly investigated (Gupta et al., 2022; Kuroda, 2021; Madl & O'Neill, 2022). The following summarises the immunological response: Particles deposited within the lung are found by pulmonary macrophages¹ that attempt to phagocytose² the foreign object, that, in turn produces a response of different interleukins and the inflammatory cytokine tumour necrosis factor alpha (TNF-α). If the particle has a high aspect ratio and is sufficiently long, the macrophages may be unsuccessful in engulfing the particle, causing cell death, described by the term “frustrated phagocytosis”. Furthermore, the chemical composition of the particle, e.g. containing iron or even attached transition metals, can cause the production of reactive oxygen and nitrogen species (ROS/RNS). The overproduction of these immune responses can lead to the diseases mentioned in Section 1.2.1.1 but can be prevented by the chemical or mechanical clearing of the foreign particles.

Asbestos was originally widely considered to be safe, to the extent that it was used to manufacture some cigarette filters in the mid-1950s (Asbestos.com, 2025), amongst other products mentioned in Section 1.1. However, with the mounting evidence against this claim, alternative, safer materials were desired, leading to further toxicology studies on similar fibres, such as erionite, mordenite, wollastonite, single- and multi-walled carbon nanotubes (SW/MW CNTs), etc. Several comparisons of other fibres have been made (Di Giuseppe, 2020; Donaldson & Tran, 2004; Fukushima et al., 2023; Gupta et al., 2022; Kuroda, 2021; Madl & O'Neill, 2022), including comparisons between different asbestos types (Mirata et al., 2022; Sen, 2015). In most cases the alternative fibres, such as synthetic vitreous fibres (SVFs), glass, rock, and slag wools, refractory ceramic fibres (RCFs), carbon fibres (e.g. SWCNTs and MWCNTs), and other mineral fibres, have shown similar, but lessened toxicological effects when compared with asbestos (Donaldson & Tran, 2004). However, there are some examples that show this is not always correct. Gupta et al. (2022), compare the immunological response of SWCNTs, MWCNTs, and crocidolite asbestos, where straight CNTs were shown to produce a greater inflammatory response than tangled/curved CNTs or asbestos. This was attributed to the transition metal residue on the CNTs used for synthesis, even after purification. Kuroda (2021) compares the toxicological effect of erionite to show similar results to that of asbestos, mordenite, and CNTs, concluding the main cause to be associated with fibre length and frustrated phagocytosis.

1.2.2 Deposition Mechanisms

1.2.2.1 Inhalation and Aerosol Deposition

Deposition of aerosol within the lungs is governed, mainly, by the aerodynamic equivalent diameter (D_a) of the particle and is found by equating gravitational (F_g) and drag (F_d) forces:

$$F_g = F_d = m_p g = \rho_p \frac{\pi}{6} D_v^3 g = \frac{3\pi\mu v_{ts}\chi D_v}{C_c(D_v)}$$

Equation 1.1

¹ A type of white blood cell.

² Engulf and remove or destroy foreign matter.

where m is mass, $g = 9.8ms^{-2}$ is acceleration due to gravity, ρ is density, μ is the dynamic viscosity (i.e., the kinematic viscosity ν , divided by the density of the surrounding medium – in this case air), v is velocity and the subscript ts indicates the terminal settling velocity, χ is the dynamic shape factor, D is diameter and the subscript v indicates it is the volumetric equivalent, and C_c is the Cunningham slip correction factor and is a function of D_v . The subscripts p and 0 refer to the particle and surrounding medium respectively. The aerodynamic equivalent diameter is the diameter of a spherical particle of $\rho_0 = 1g \cdot cm^{-3}$ (i.e., unity density) that has the same terminal settling velocity of the particle in question. Rearranging Equation 1.1 for v_{ts} then gives:

$$v_{ts} = \frac{\rho_p g C_c(D_v) D_v^2}{12\mu\chi} = \frac{\rho_0 g C_c(D_a) D_a^2}{12\mu}$$

Equation 1.2

where the dynamic shape factor for a sphere is unity. Finally, D_a can be found:

$$D_a = D_v \left(\frac{1}{\chi} \frac{\rho_p}{\rho_0} \frac{C_c(D_v)}{C_c(D_a)} \right)^{\frac{1}{2}}$$

Equation 1.3

The D_a will then dictate what section of the lung the aerosol will most likely be deposited in: the extrathoracic region consisting of the mouth, nasal passages and larynx; the tracheobronchial region from the trachea to the terminal bronchioles; and the alveolar-interstitial or pulmonary region where gas exchange occurs. These areas are indicated in Figure 1.1. The deposition will occur through different mechanisms: impaction for the large ($\sim 8 \mu m$) particles in the extrathoracic region, sedimentation for the medium ($\sim 5 \mu m$) particles in the tracheobronchial region, and Brownian motion for the small ($< 1 \mu m$) in the pulmonary region. This is, however, a simplistic view of the size ranges and areas of deposition; distributions of particle sizes are found in different pulmonary regions, and a percentage of the aerosol is not deposited and then exhaled, as discussed by Newman (1985).

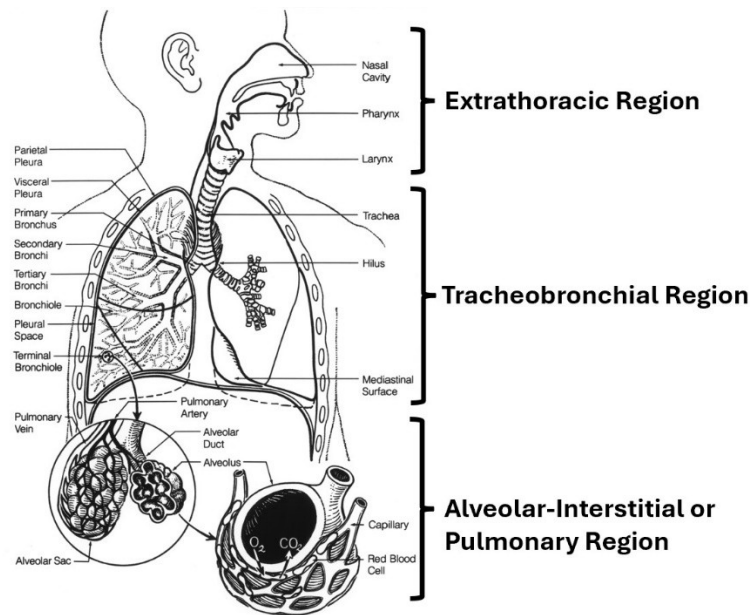


Figure 1.1: Illustration of the human respiratory system, highlighting the extrathoracic, tracheobronchial, and pulmonary regions. Adapted from National Cancer Institute (2001).

Many other factors will influence the deposition location, not just the aerodynamic diameter. This includes aerosol properties such as particle charge, where the electrical mobility of the particle can influence the deposition, depending on the charge of the deposition surface. Considering environmental properties where the ambient relative humidity is normal (around 50% for the UK), the relative humidity inside the human lung is above 99% and so, when aerosol enters the respiratory system particles can become nucleation sites for hygroscopic growth. This causes water vapour to condense on the particles, resulting in a larger diameter, but will also depend on the hydrophobicity of the particles. Considering materials such as asbestos contain hydrophobic groups within their chemical structure, as explained by Meng et al. (2025), the reduction in the materials wettability may prevent any potential hygroscopic effects. However, water spray is used during work with asbestos to reduce the amount of airborne fibres and so may need to be considered when using light scattering techniques as a means of measurement or detection.

Much research has gone into the modelling of aerosol inhalation within the lungs, with considerations of many factors as mentioned and others such as the morphology of the respiratory tract (Hofmann, 2011). These factors, however, are not completely necessary to help understand the principles of this project and have only been mentioned to highlight the overall complexity of aerosol deposition mechanisms.

1.2.2.2 Fibre Dynamics

For fibres, the aerodynamic equivalent diameter still depends on Equation 1.2, however, the dynamic shape factor will be heavily dependent on the orientation of the fibre, relative to the direction of flow and the regime of the flow it is in. This only adds to the complexity of an already complex problem. Jianzhong et al. (2004) have shown that the orientation of the fibre itself is dependent on the flow regime, the Reynolds number, and the shear rate of the flow, whereas density or aspect ratio of the fibre have negligible effects on the fibre orientation. Their investigation used numerically simulated laminar and turbulent pipe flows to determine the oriental behaviour of the fibres within. The diameter of the fibres, however, were 1 mm and so may not be representative of the fibres in the respirable size range. Stopford et al. (2013)

measured the orientational data of ~2000 respirable fibres in a laminar flow, of a parabolic profile, and found that 86% of the fibres were aligned within $\pm 10^\circ$ of the flow direction.

1.2.3 Sources of Fibres

Exposure to man-made mineral fibres (MMMFs) is a serious problem that can't be immediately solved by its banning or removal. Air-quality monitoring is essential for prevention, or at least reduction, of exposure. Additionally, considering the ambiguity of toxicity between different materials, and to follow with the World Health Organisation (WHO) guidelines (see Section 1.2.4.1), fibre size measurement would provide the more desirable means of detection.

1.2.3.1 Asbestos Exposure

The detection of fibres deposited within the lung is difficult and exposure is normally only discovered after the development of severe inflammation or disease. Considering mesothelioma cases from asbestos exposure, Furuya et al. (2018) show a steady increase in known cases between the 1980s and 2015, but deaths are predicted to decrease in the future. More recently, X. Li et al. (2024) report a decrease in age-standardised mortality rates between 1990 and 2019 in the US however, they also report around a 20% increase in death related to occupational exposure to asbestos in that time.

Exposure to respirable fibres can occur in many places. As an example, the banning of the use of asbestos was made in the UK through various regulations made between 1969 and 1993 giving rise to the possibility of asbestos present in buildings constructed from around the 1950s (and most likely before that) to the latest ban date. Additionally, as mentioned in Section 1.1, the popularity of the material led to its use in many products, including set props and was used as snow (Bronkema, 1988) and a broomstick (Alleman & Mossman, 1997) in the 1939 film "The Wizard of Oz". As mentioned previously, many buildings constructed at prior to the imposition of bans may have been built with asbestos-containing materials (ACM), such as reinforced concrete. Some asbestos fibres may become airborne without any known influence, such as the dwellings investigated by Pastuszka (2009), or from the refurbishment of buildings containing ACM (Ervik et al., 2023) due to the natural degradation of the materials. Asbestos can also be aerosolised from contaminated soil, as investigated by Jones et al. (2010), examining the re-aerosolisation of soil samples in proximity to a disused asbestos mine. Further, brownfield sites, previously developed industrial land, may also contain ACM that poses the risk of re-aerosolisation of asbestos (Hellawell & Hughes, 2021).

1.2.3.2 Non-Asbestos Exposure

Wollastonite has proved to be a popular replacement for asbestos (Maxim & McConnell, 2005) and can be both found in naturally occurring forms and synthesised (Kotsis & Balogh, 1989). Naturally occurring wollastonite is found in small amounts and usually contaminated with other minerals, making synthesis of the material a more desirable prospect. The process, involving heating of a precursor material, however, creates the wollastonite with a slightly different composition than the naturally occurring one. The mining and synthesis of wollastonite, and indeed any other similar mineral fibre, would be a potential source of exposure.

Respirable carbon fibre is found in the aerospace, automotive, civil engineering, and energy industries (Meyer-Plath et al., 2023), or from, for example, the manufacturing or mechanical processing of carbon fibre reinforced polymers (Kehren et al., 2019). The process in manufacturing carbon fibres, first produced around 1880, has been continuously developed since the beginning of the 1960s (Paris & Peterlik, 2009). Since this time, variations in

production methods are now used but the basic principles are explained by X. H. Zhang & Li (2017). Powder or granular forms of the precursor material are converted to fibres via a spinning process. There are different methods of spinning which depends on the precursor material.

Considering fibres such as refractory ceramic fibres (RCF), again, the most likely source of exposure would be from the manufacturing process itself, but also potentially any installation, maintenance, or removal of RCF-containing products such as furnace insulation (Maxim & Utell, 2018). The manufacture processes of RCF and rock or slag wool are relatively similar to those of carbon fibres, discussed by Lemasters et al. (1998) and Cherrie et al. (1987), where a precursor is heated and spun by various means. The manufacture of glass fibres, however, is undertaken by heating the bulk glass material to retain the glass at a constant viscosity. The glass falls under gravity and is collected using bushes that guide the fibres to a bundle, as described by Thomason (2019).

1.2.3.3 Micro-Machined Fibres

An alternative source of high aspect ratio micro-particles, manufactured as a means of testing light scattering instruments, are described by P. H. Kaye, Micheli, Tracey, Hirst, & Gundalch (1992). Their work demonstrated the process in manufacturing particles of silicon dioxide and polycrystalline silica of uniform shape and size – all having a square cross-section of $\sim 1\ \mu\text{m}$. The process involved the computer-aided designing (CAD) of the particle profiles and their photolithographic masking and etching of silicon wafers, similar to the process of manufacturing integrated circuits. The remaining material, i.e., particles, are removed from the substrate that backed the wafers by a chemical process to finish with a suspension of uniform particles. These particles, amongst others, were subsequently aerosolised by P. H. Kaye, Hirst, et al. (1992) to investigate their light scattering profiles. Unfortunately, it has been found that the aerosolisation of these fibres becomes extremely difficult for lengths beyond $3\ \mu\text{m}$.

1.2.4 Regulations

1.2.4.1 WHO/NIOSH Regulations

The basic size requirements for respirable fibres are outlined by the WHO as having a diameter of less than $3\ \mu\text{m}$, a length greater than $5\ \mu\text{m}$, and an aspect ratio greater than 3:1 (World Health Organisation, 1985). The procedure and rules for the collection, preparation, and evaluation of the fibres are also outlined and are as follows.

Currently, the evaluation of Man-Made Mineral Fibres (MMMF) exposure is conducted off-line, using either optical or electron microscopy investigations from filter samples. Volumes of air from potentially contaminated sites are passed through filters and sent to laboratories to be manually evaluated. Fibre count is determined through phase contrast optical microscopy (PCOM) wherein certain counting rules are applied, depending on location and will be explained in this section. Fibre composition, however, requires either scanning or transmission electron microscopy (SEM/TEM) along with energy dispersive x-ray spectroscopy (EDX). Both methods require trained operators and can take around 24 hours for a result (Iles & Shenton-Taylor, 1986). The results may also vary depending on the laboratory and its operators.

Both the WHO and the National Institute of Occupational Safety and Health (NIOSH) have detailed reference methods on the procedure for collecting and counting asbestos and other MMMFs. The collection of fibres to monitor potential exposure is conducted using a small, battery powered device where the sample inlet is located within a 300 mm radius of the operator's nose, i.e., their "breathing zone". The device used had a belt-worn pump and a tube attached to the operator's lapel, where the filter is located. The sample is collected over an 8-

hour shift with a flow rate between 0.5 L/min and 2 L/min, adjusted to collect an estimated fibre count between 50 fibres/mm² and 1000 fibres/mm² as a way of minimising counting errors. The filter used is a 25 mm diameter gridded cellulose ester with a 1.2 µm pore size.

After the samples are collected the filters are mounted on microscope slides using the acetone-triacetin method. Boiling acetone is used to create a jet of vapor that renders the filter material transparent³, then a small amount of glycerol triacetate is used to help cover the sample with a coverslip, for better optical contact. It is also noted that this method is unsuitable for materials with refractive indices between 1.43 and 1.49, presumably due to the refractive index of the now cleared filter. No mention of the imaginary part was included and so not considered a major limitation. Counting is then performed using PCOM at a magnification at around 500× by a trained operative with good eyesight, after robust calibration has been carried out. A minimum of 20 graticule areas are then observed, up to 100 areas, and up to a count of 100 fibres in order to estimate the total fibre count. The lengths of any curved fibres found are measured along the curve. Further, the diameters are measured at an average point, fibres wholly within the graticule are counted as one fibre, fibre ends in the graticule are counted as a half, and fibres with no ends within the graticule are not counted. Fibres with split ends are counted as one, clumps of material not easily distinguished are not counted, and fibres in contact with other material should be counted as if that additional material is not present. The NIOSH 7400 B rules on counting are largely similar, slight differences in flow rate and estimated fibre count are mentioned, including indistinguishable fibre bundles counted as one, contrast to the WHO rules. Additionally, more details of methodology are included, such as how to randomly move the graticule to a new area and the amount of time it should take to count in each area. An updated WHO counting rules were published in 1997 where additional methods of mounting the samples were described, however, aside from some small changes, nothing much is different to the previous description.

1.2.4.2 Interlaboratory Comparisons

To maintain consistency between, and within, counting laboratories, many different testing schemes are implemented. Britain's Health and Safety Executive (HSE) use the Regular Interlaboratory Counting Exchange (RICE) and Spain's Instituto Nacional de Seguridad y Salud en el Trabajo (INSST) use the Programa Interlaboratorios de Control de Calidad de Fibras de Amianto (PICC-FA). International schemes are also in place, such as the Asbestos Fibre Regular Informal Counting Arrangement (AFRICA), that also help laboratories compare their own counting standards.

Many problems can lead to under- or over-estimation in fibre count: thin fibres (< 0.2 µm – 0.3 µm) not seen via PCOM, interpretation of counting rules, instrumentation quality, varying magnifications in SEM, and different problems regarding the operator/microscopist (Crawford et al., 1987; Elovskaja & Kovalevsky, 2002; Grzebyk et al., 2005; Harper & Bartolucci, 2003; Jones et al., 2005). Crawford et al. (1987) demonstrate the importance of using a single reference method by comparing counts from five different laboratories using different counting methods at the time of publication of the new WHO reference scheme (World Health Organisation, 1997). Laboratories showed a decrease in variation of counting results when using the same WHO scheme, unfortunately there was still a notable difference in the reported geometric mean length of fibres from the different laboratories. Comparisons between results of laboratories counting under different regulations have also been investigated. Breyse et al.

³ Also known as clearing.

(1994) show a statistical significance in reported fibre density between five European laboratories using the WHO reference scheme and five American laboratories using the NIOSH scheme. As these schemes are different, a difference in fibre count would be expected, however, the laboratories using the NIOSH scheme reported counts which were 27% less than the laboratories operating under the WHO scheme.

Jones et al. (2005) also compares counting results (similar to the processes undertaken by AFRICA) between laboratories operating under different proficiency testing schemes: RICE, PICC-FA, and a scheme used in Belgium. They also compared the difference in fibre count when using the old European Reference Method (ERM) and the newer WHO method. The difference between the ERM and WHO methods is that the WHO method now counts fibres attached to particles $> 3 \mu\text{m}$ in diameter. Differences in counts between operators were found but there were considerably fewer differences between laboratories and, unsurprisingly, there was a similar percentage increase of fibre counts between the two reference methods. The average difference in counting levels between national schemes were shown to be around 5% and a similar investigation by Grzebyk et al. (2005), echoed similar results but also proposed considerations to adapt the Workplace Analysis Scheme for Proficiency (WASP – since changed to Air & Stack Emissions Proficiency Testing – AIR PT), that could help synchronise counting results between laboratories. Harper & Bartolucci (2003) demonstrate variations of counting between operators using the same NIOSH reference scheme, comparing six microscopists' results of twelve fibre samples counted from the same grid reference area. Operators were found to miscount fibres close to the size limits, undercount fibres with small diameters, and mistake scratches on the slides as fibres. However, excluding the two operators having counts regarded as outliers, for each fibre type the pooled standard deviations of the variations with respect to the consensus value (a “true value” agreed by several laboratories) fell within the 95% confidence limit.

More recently, Rabiee et al. (2023), demonstrate the ability of machine learning neural networks to count fibres from filter images in an attempt to speed up the counting procedure and reduce operator errors. The samples were collected on mixed cellulose ester filters and needed no complex preparation like that used in the standard counting methods. Results of their method showed a reasonably good interpretation of fibre counting trained using the NIOSH 7400 method, with less precise results for more complex fibres like branched or agglomerated. Unfortunately, there was difficulty in identifying fibres of small diameter ($< 0.7 \mu\text{m}$).

1.3 Instrumentation

1.3.1 Basic Aerosol Monitoring

Considering the dangers associated with respirable fibres, the possibility of unintentional exposure, the timescale and difficulty in counting and identifying them, and the ambiguity shown between microscopists, laboratories, and national proficiency schemes, more immediate protection needs to be implemented. Investigations of methods and instrumentation for the detection and measurement of aerosols have been conducted since the late 19th century when John Tyndall used intense light to detect particulates when conducting environmental experiments.

There are several different methods and types of instrumentation used to monitor air quality. Hasheminasab et al. (2017) outlines a few techniques including gravimetric measurements, where a filter is weighed pre- and post-collection based on the density of particles and the time

and flow rate of collection, giving a time-averaged measurement. An ultrasonic sensor is also described, wherein the attenuation of soundwaves through a particle-laden suspension is used to find the particle size distribution. However, the main focus of their paper is on using different optical fibre arrangements to measure the volumetric fraction of aerosol within a chamber. These techniques are a valid way to monitor aerosol concentrations using either time- or volume-averaged methods. However, by using other instrumentation, single particle measurements can be made for a more detailed overview of the ambient air. Higher accuracy in time resolution and size distribution can be found, even at lower particle concentrations.

1.3.2 Optical-Based Particle Counters

1.3.2.1 OPC Working Mechanisms

For lower concentration measurements, and to achieve a higher time resolution and size distribution, single particle counting and sizing can be made with a plethora of instrumentation, all using various methods to detect and size aerosolised particulates. The most basic of which, using solely light scattering, is an optical particle counter (OPC). The basic working principles of these are described by Baron (1994) wherein a light source is focused to an area intersecting an aerosol flow, defining what is called the scattering volume, and a light sensor is used to measure intensity and duration of scattered light within a pre-defined solid angle. The intensity and duration of the pulse, measured by the light sensor, is used to determine the size of the aerosol after using known samples as a means of calibration. There is a caveat; these measurements usually assume a volume equivalent diameter, i.e., the assumption that each particle is perfectly spherical, along with the assumption of a fixed density and refractive index, all of which can affect either the light scattering or the time of flight (ToF).

Instruments that are based on these working principles include the OPC-N3 and OPC-R2 (Alphasense Ltd.), the Universal Cloud and Aerosol Sounding System (UCASS, Smith et al. (2019)), the Optical Particle Sizer (OPS) 3330 (TSI Inc.), the SPS30 (Sensirion AG), the WPMA115S0 (Honeywell International Inc.) the SDS018 (Nova Fitness Co. Ltd.), and the PMS5003 (Nanchang Panteng Technology Co., Ltd. a.k.a. Plantower). There are, however, limitations on size range, e.g. the UCASS (low gain) can detect particles of diameter 1 μm to 40 μm . Smaller particles are indistinguishable from noise, and larger particles saturate the photodetector. The UCASS (high gain), however, shifts the dynamic range for smaller diameters but requires alterations to the circuitry and reduces the upper size limit, demonstrating the limitations of the OPC's photodetector. The allure of the low-cost OPC devices is not only the stark price difference that can be found compared with more high-end devices, but also the size and portability that ensues. A summary of the different OPCs on detectable size range and physical size are shown in Table 1.1.

Model	Manufacturer	Lower Size / μm	Upper Size / μm	Height /mm	Width /mm	Depth /mm
OPC-N3	Alphasense	0.38	17	63	60	76
OPC-R2	Alphasense	0.3	12.4	21	21	71
UCASS - Low-gain	N/A	1	40	184	64	64
UCASS - High-gain	N/A	0.4	17	184	64	64
OPS-3330	TSI	0.3	10	120	210	255
SPS30	Sensirion	0.3	10	12	41	41
WPMA115S0	Honeywell	0.3	10	24	36	43
SDS018	Nova Fitness	0.3	10	20	45	59
PMS5003	Plantower	0.3	10	21	38	50

Table 1.1: Summary of various OPCs, including particle size range and physical dimensions.

Several comparisons have been made to assess the performance of these devices (e.g. Bulot et al., 2020; Hagan & Kroll, 2020; Markowicz & Chiliński, 2020; Nurowska et al., 2023) and seem to show a general under-sizing of aerosol, difficulties with high relative humidity, and a more limited size range when compared to more advanced instrumentation.

Few studies have been conducted to assess the impact of particle shape or refractive index on the size reported by OPCs. The effect of shape has been analysed with the OPC Wellas 3000 (PALAS GMBH) using irregular shaped SiO_2 particles by Lu et al. (2022). By heating the aerosolised SiO_2 particles, melting them to form spheres, a comparison of mass concentration was found to have only a 2.94% difference. Often, however, they are used to report a total Particulate Matter (PM) concentration that aligns with more traditional gravimetric analysis. This also makes the OPC dependent on assumed (or a priori) knowledge of the particle density. The effect of both shape and refractive index on OPCs are under-studied and worth further investigation.

1.3.2.2 Extended Size Ranges

A greater dynamic size range can be detected by more sophisticated instrumentation, at the price of a greater physical size and monetary cost. For example, the Aerodynamic Particle Sizer (APS) 3320 (TSI Inc.) uses the combination of light scattering and particle acceleration to more accurately determine particle size (Baron (1994)), with a range that extends from 0.5 μm to 30 μm . The APS-3320 measures $\sim 190 \times 368 \times 320$ mm and is around an order of magnitude more expensive than the devices mentioned in Section 1.3.2.1. Unfortunately, as the particles are accelerated, liquid droplets can easily deform and result in under-sizing. Additionally, compensations have to be made to adjust to particle density and shape. For the detection of smaller particles, other instrumentation designs can be made, such as condensation particle counters/sizers (CPC/CPS), e.g. the 5210-CPC (Cambustion, Ltd.) can measure particle sizes from 5 nm to 10 μm . These instruments still use the basic principle of light scattering for detection and measurement. However, the ability to detect and measure smaller particles is made by using the aerosol as condensation nuclei that are passed through a saturated environment, causing vapour to condense onto them and grow large enough for detection. Unfortunately, CPCs are only used for total particle number concentration, any particle size analysis requires additional equipment such as a Differential Mobility Analyser (DMA). The primary function of these instruments is to monitor the ambient air quality and are largely referred to as dust monitors.

Several different dust monitoring instruments have been compared, and this has highlighted some potential problems. Görner et al. (2001) compares fifteen different aerosol samplers with

the APS 3300⁴ using coal dust, chosen as eight of the samplers were designed for coal-mining operations, to determine their sampling efficiency. The results showed the inherent differences of sampling efficiencies that can occur between different instruments and therefore results. The main conclusion was the need for a priori information, the user must make the correct selection and optimise the instrument tailored to the required task. Other potential problems were highlighted by Thorpe (2007), who compared five different dust monitors in a wind tunnel with a cyclone sampler using aluminium oxide powder, stone dust, and wood dust. The dust concentration was compared and showed that the light scattering-based devices either over- or under-estimated this compared to the cyclone samplers but were reported to work much better with dust within the respirable size range. Different problems for the different monitors tested highlighted some possible design problems such as leakage, inlet morphology, and contaminated optics. Consistency between the same instruments is important for verification. Susz et al. (2020), compares three DustTrak DRX (TSI Inc.) instruments with gravimetric measurements using ambient air, polystyrene latex spheres (PSL), and environmental tobacco smoke. Their investigation highlighted how most optical-based aerosol monitors won't differentiate between solid and liquid aerosol. The difference in results from the DustTrak units are explained by their lack of sensitivity beyond certain size limits. Inter-comparisons of the units themselves also showed differences, explained with possible vibration interference from transportation, or calibration issues. However, after applying a photometric calibration factor, the authors conclude that the DustTrak can measure aerosol particulate matter (PM) levels within suitable tolerances.

Unfortunately, for a greater comprehension into the aerosol type and the potential hazard that could follow from exposure, more information than size and concentration distributions about the aerosol are required. As mentioned previously, post-filter collection analysis is commonplace for fibres but is also used for other respirable hazards such as Respirable Crystalline Silica (RCS). Cauda et al. (2022) investigates RCS exposure at a quarry using cyclonic samplers, video recordings, and Fourier-Transform Infrared Spectroscopy (FTIR). The cyclone samplers gave time-integrated readings of the dust levels that were compared against gravimetric readings of a filter within the sampler. The filter was also analysed using FTIR to evaluate the percentage of RCS. The video monitoring was used to help identify possible sources of exposure. Although the identification and percentage of the RCS was conducted post-collection, the FTIR method proved to be comparable to the traditional method. More recently, Romadhon et al. (2023), describes an OPC that measures both particle size and refractive index. The instrument uses a combination of a linear array of photosensors and a photomultiplier tube (PMT) to detect and measure aerosol. The PMT measures the light scattered by any aerosol within a set solid angle and is calibrated for size measurements, just as a regular OPC operates, with the highest efficiency between sizes of 1.6 μm – 6.1 μm . The linear array measures the scattering pattern made by the aerosol from 37° – 144° of the light propagation direction and a combination of that response and that of the PMT, a particle size and refractive index was found using a lookup table. The added information of the aerosol's refractive index could prove extremely useful in the identification of aerosol type. Unfortunately, there are a few drawbacks: the large size and weight makes this instrument field-deployable only; a non-absorbing, spherical particle is assumed; and laboratory testing only used PSL of a single refractive index.

⁴ Similar to the 3320 model.

1.3.3 Bio-Detection

Distinctions between biological and non-biological, or between different types of biological, aerosol can be determined with the use of light induced fluorescence. Most organic, biological aerosol contain fluorophores such as tryptophan and nicotinamide adenine dinucleotide + hydrogen (NADH), that fluoresce around a particular wavelength (depending on the incident radiation). P. H. Kaye et al. (2004) describe the Wide Issue Bio-aerosol Sensor (WIBS) and its working principles; ambient air is drawn into a chamber at 10 L/min where two xenon flash bulbs illuminate the particle 300 ms apart. Fluorescence emissions can then be detected using one of two PMTs. Excitation and emission wavebands are defined by optical filters over the xenon flashlamps and the PMTs. Different bio-aerosol samples were used in testing, and by plotting each sample as a function of the response of both PMT channels, a clear definition can be made between different test samples, such as ovalbumin and bacillus globuli (BG). The WIBS was then improved upon with the inclusion of a continuous-wave diode laser, that both triggered the xenon bulbs but also acted as an OPC to give size information (P. H. Kaye et al., 2005). Additional test samples were used, such as E. coli and tonic water (containing quinine), and showed just as successful results as the previous version regarding fluorescence. Little was commented on with regards to size data, an APS-3330 was used to monitor mean size and particle concentration, however the results displayed as functions of both fluorescence channels and size provided superior definition between samples, compared with the previous version.

Many other devices use this basic principle of fluorescence detection for bioaerosol. The Ultra-Violet Aerosol Particle Sizer (UV APS, TSI Inc.) has the same working principles but is limited by time resolution and a single fluorescence detection channel. An improved version of the WIBS was made by Droplet Measurement Technologies, the Spectral Intensity Bioaerosol Sensor (SIBS), by replacing the 8-channel PMT fluorescence detection with a 16-channel one. The Multiparameter Bioaerosol Sensor (MBS, Ruske et al. (2017)) incorporates additional spatial light scattering information, using linear arrays, for a more accurate determination of the bioaerosol using machine learning algorithms.

1.3.4 Fibre Monitors

Other aerosol monitoring equipment, specifically designed to detect, count, and measure fibrous aerosol, have been made and rigorously compared to the standard counting methods. Each of these instruments uses a secondary artefact of the aerosol, beyond light scattering.

1.3.4.1 *Electrostatic Alignment*

The one method most commonly used for detection and measurement of fibrous aerosol is the electric charge-induced alignment of fibres within a flow, coupled with light scattering. Iles & Shenton-Taylor (1986) overviews the working principles behind the fibrous aerosol monitor FAM (GCA Corporation) and other similar instruments are described by Baron (1994) (FAM-1 and FM-7400; MIE Inc., Bedford, Massachusetts), Kauffer et al. (2003) (FM-7400, FibreCheck FC-2; Harley Scientific), Pastuszka et al. (1999) (FM-7400). Ambient air is pumped through the instrument along a tube in which a laser is collimated. As aerosol passes through the tube, scattered light is detected by a PMT at 90° to the direction of light propagation. Simultaneously, depending on the model, either a single oscillating electric field or two alternating electric fields are applied. As the aerosol passes along the tube, the two electric fields are alternately activated (or the single field oscillates), causing any fibrous material to rotate to align with the field. Laser light is scattered by any particles traversing the tube and, as fibres scatter light

perpendicular to their major axis, a PMT will measure a pulsed response from rotating fibres. The FAM instruments use these pulsed responses to discriminate fibrous from non-fibrous material (no pulsed response) and the fibres' size, based on the intensity and duration of the pulse. Another fibre monitoring system was also mentioned by Baron (1994), the FACT-1000 (Hygienius, Canada) and how it used similar principles to the FAM instruments but used scattering patterns of the fibres to classify fibres by length and diameter. Unfortunately, this was under development at the time of publication and no further information was found.

Iles & Shenton-Taylor (1986), compares the Fibrous Aerosol Monitor (FAM; GCA Corporation) to the standard membrane filter method at the time (no mention of specific technique) and a Royco OPC (no information given on model). Comparisons with the membrane filter method showed an increase in ratio count for fibres/ml when using FAM, i.e., the FAM instrument counted around five times more by the end of an 18-month period. The possibility of miscounting through the filter method was ruled out due to several quality assurance measures. Poor results were found when testing under factory conditions wherein both fibrous and non-fibrous aerosol were present and later confirmed, under laboratory conditions, to show a massive over-count of particles. When compared with the Royco OPC, an instrument designed to count particles and not distinguish between shape, the FAM showed comparable results. Finally, a second FAM was also tested, but results compared with the filter method indicated to a fault with the instrument and no further testing was performed. Spurny (1994), also investigates both the FAM and the FM-7400, echoing a similar conclusion of poor FAM and PCOM comparisons, but also highlighting how both the instrumentation and PCOM methods only provide an index of exposure and are not truly representative of the potential respirable fibrous hazards. Additionally, as peaks from the gold coating used in X-ray analysis overlap with that of silicon, EDX is not completely reliable in distinguishing different asbestos types, or other silicon-containing fibres.

Many more comparisons and tests have been conducted using the newer FM-7400 model. Kauffer et al. (2003), compares both the FM-7400 (Newer FAM model to correspond with the NIOSH 7400 counting rules) and the FibreCheck FC-2 (latest model was the HS FC6 by Harley Scientific Ltd.) with PCOM to determine how well they agree with standard counting procedures. This was done by carrying out field tests in MMMF production plants that manufacture ceramic and slag wool fibres, chrysotile was also tested but under laboratory conditions. It was shown that the FC-2 greatly overexaggerated counts regarding MMMFs; struggled to operate correctly below a relative humidity of 30%; and lacked sensitivity for low concentrations. The FM-7400 was shown to be more difficult to use, but agreed quite well with PCOM results for chrysotile. Pastuszka et al. (1999) also compares the results of the FM-7400 to the standard PCOM method for asbestos exposure in a number of different dwellings in Poland. Unfortunately, the PCOM analysis proved inconclusive due to the amount of non-fibrous particles masking the majority of the sample. This was then re-visited ten years later by Pastuszka (2009), in a similar investigation, showing very poor comparisons between the FM-7400 and PCOM results.

1.3.4.2 Multi-Fibre Light Scattering

Rood et al. (1992), describes another portable fibre monitor that uses light scattering from flow-aligned fibres deposited on a substrate using corona charging. The sampled aerosol is passed through a corona wind and are deposited onto a microscope slide. A green light emitting diode (LED) is collimated to a 3 mm spot at the area of deposition and photosensors monitor the scattered light level. Calibration is made by the fibre count made with PCOM. The findings indicated that fibres below an aspect ratio of 4:1 showed a random orientation, and that for chrysotile (being curved and prone to aggregation) displayed an overall alignment but was

difficult to visually assess. Additionally, a payoff between fibre deposition and alignment was explored due to the corona current, a higher current produced more deposition but also poorer fibre alignment. However, from experimenting with different aerosolised dusts, a clear definition from fibrous and non-fibrous material can be seen. Unfortunately, this instrument has not been as vigorously tested, compared to the FM-7400.

1.3.4.3 *Single-Fibre Magnetic Alignment*

Another purpose-built fibre monitoring system, to detect and distinguish asbestos from other fibrous aerosol (e.g. gypsum) was described and tested by Stopford et al. (2013). The light scattering patterns from fibres are very distinct, and asbestos contains minerals that give it paramagnetic properties. This asbestos detection system, that uses the combination of scattered light and magnetic re-alignment, was later developed into the ALERT Pro-1000 asbestos detector (discontinued).

Fibres are loosely aligned with the sample airflow and then introduced to a laser beam. The orientation of the fibre is measured based on the spatial scattering pattern. As the particle moves out of the first laser, it enters a permanent magnetic field orthogonal to the flow. Paramagnetic asbestos fibres are realigned to the field, whilst non-asbestos fibres are not. A second laser beam is used to produce another scattering pattern, which can be compared to the first in order to measure the rotation of the fibre due to the magnetic field.

A rotation angle of more than 20° suggests an individual fibre is six times more likely to be asbestos than non-asbestos, although a statistical measure of a population of fibres is used to indicate the presence of asbestos. However, this depends on the asbestos to non-asbestos concentrations and false positives are more likely to occur in a higher non-asbestos fibre environment, e.g. for a detection of chrysotile with 99% confidence, the chrysotile should make up around 45% of the fibre population. This was originally intended to be a low-cost warning system for tradespeople who are at most risk of exposure. No morphological information of the asbestos is calculated, beyond a binary threshold of “fibre” and “non-fibre”, and so to determine the level of the respirable fraction, traditional methods still need to be used.

1.3.5 Spatially Resolved Light Scattering Instruments

1.3.5.1 *Working Principles*

Instruments have been developed to study the morphology of single⁵ aerosols using their spatially resolved scattered light, captured by sensors and cameras. An instrument is described by P. H. Kaye, Hirst, et al. (1992) where light scattered from aerosol and captured by a charge-coupled device (CCD) camera to be then assessed by comparisons with modelled data. 30° – 141° of the scattered light⁶ is reflected from an ellipsoidal mirror and then focused through a series of optics, the 5° – 30° of scattered light is used to trigger the CCD. Both fibrous, micromachined silicon-dioxide wafers (described in Section 1.2.3.3), and PSL spheres of single or doublet⁷ arrangement were used as test aerosol to generate scattering images. The test particles were aerosolised and pumped into a scattering chamber surrounded by a sheath flow to focus the particles into a 0.8 mm jet. The particles traverse through the focus of a helium-neon laser with an ellipsoidal cross-section of ~3 mm × 0.12 mm and scatter the incident laser light.

⁵ Including agglomerated particles.

⁶ From the propagation direction of the incident light.

⁷ Two spheres paired together, either agglomerated or slightly separated.

Very distinct features of the different aerosol types can be seen in their results; single spheres create a series of concentric rings, doublets create similar rings but from two sources with central interference fringes that depend on the separation distance, and fibres create a bright band of light. The results given were compared to numerical models and showed good results with explanations for slight differences such as particles not going through the exact centre of the beam showing a slight off-set and distortions created by the ellipsoidal mirror. Examples of these are shown in Figure 1.2, adapted from Hirst & Kaye (1996).

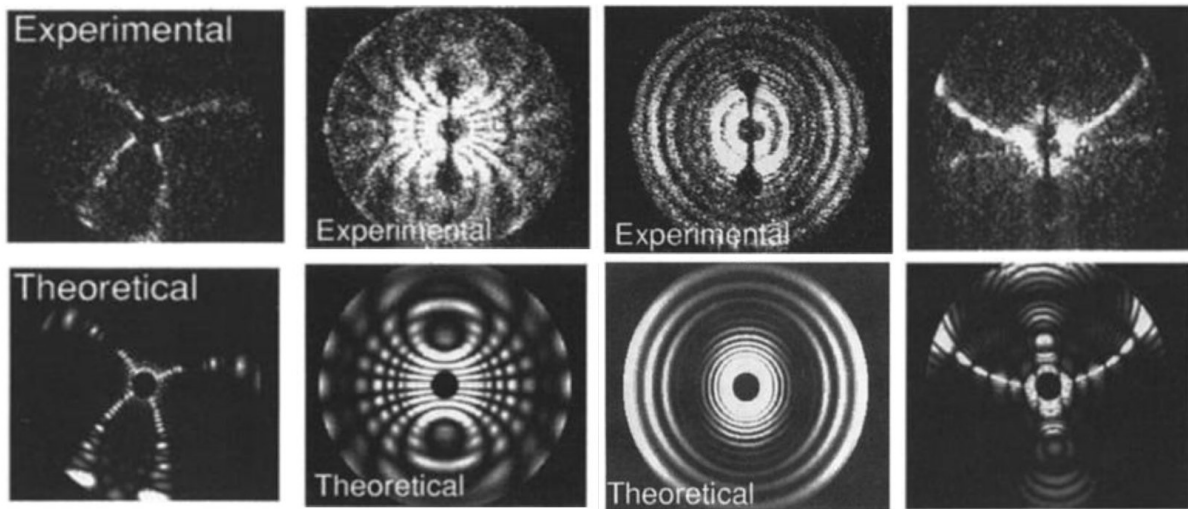


Figure 1.2: Experimental (top row) scattering and modelled (bottom row) data from a cube, doublet, droplet, and a micro-machined fibre (left to right), adapted from Hirst & Kaye (1996).

This was further built on by P. H. Kaye (1998), with descriptions of a simplified instrument that employs a segmented radial array to capture approximately 30° of the forward scattering. This eliminated the need for a large, expensive mirror and also simplified and increased the rate of the data output. Additional examples of different aerosol types, and their corresponding scattering patterns were included, such as irregular shaped background particles (amorphous dust), droplets (similar to the scattering profile of spheres), flake particles, and salt crystals. Fibrous examples were also included to highlight the differences found with chrysotile asbestos and non-chrysotile asbestos, wherein the former has a degree of curvature along the major axis, resulting in a “bowtie” pattern as opposed to a thin band. To distinguish between the different scattering types, a pre-trained neural network-based identification system was then used as a method of classification. Examples of these patterns are shown in Figure 1.3, adapted from P. H. Kaye (1998).

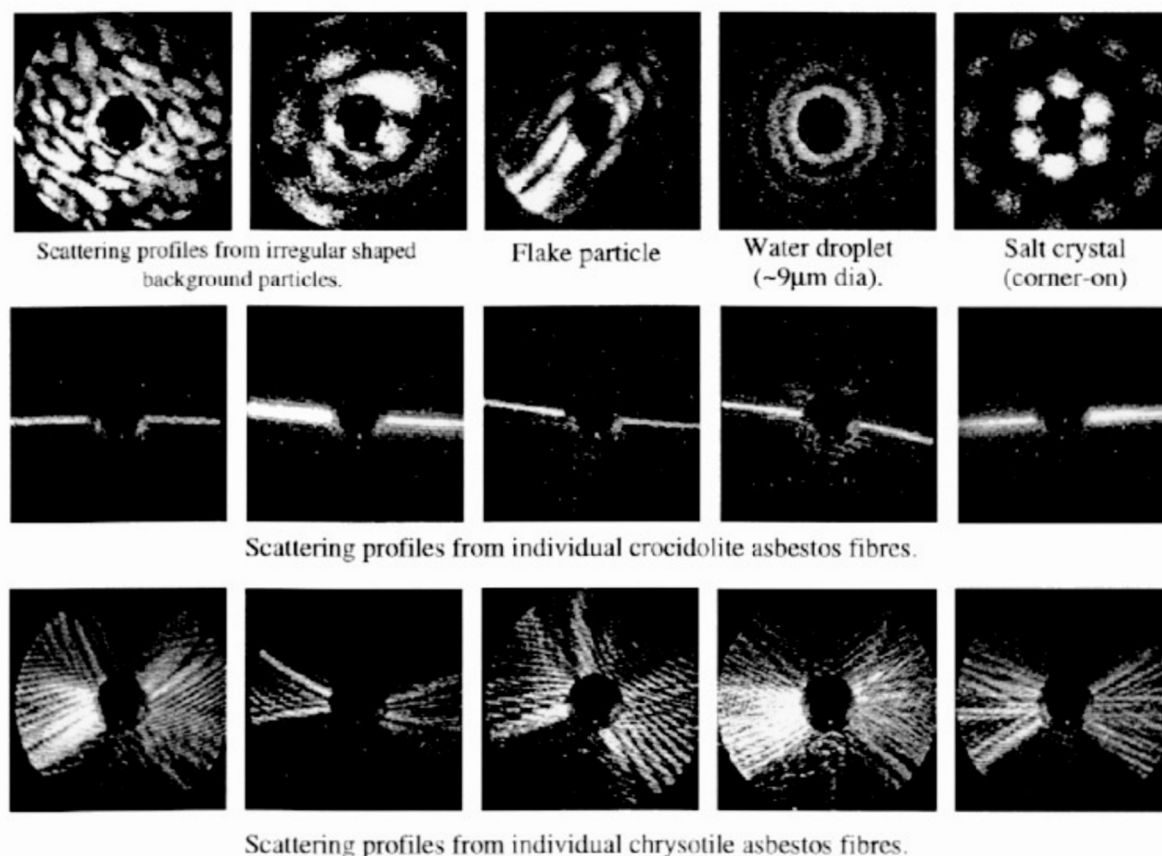


Figure 1.3: Scattering images captured, showing background laboratory air (top row) and identified as irregular dust (large and small), flake, water droplet, and a salt crystal (left to right). The middle row shows scattering examples of crocidolite asbestos and the bottom row chrysotile asbestos. Adapted from P. H. Kaye (1998).

Capturing light scattering patterns as an image from single aerosolised particles allows the opportunity to anticipate what could be detected by a simplified light scattering detection system. Images taken from cameras contain much more data relative to simple photosensitive arrays and are limited by the speed in which the data can be exported from the hardware and stored for analysis. The forward light scattering patterns of particles can be used to prototype systems with simplified light sensing abilities and still manage to identify particle properties such as size and basic morphology. The Small Ice Detector (SID, Hirst et al. (2001)) used 6 PMT detectors arranged in a ring about the forward direction and was compared to example scattering patterns. The data collected was used to measure the size and asymmetry factor of cloud particles. The second iteration of the instrument, the SID-2, increased the capability by increasing the number of detector elements to 27 radial segments, and the SID-3 employed an intensified CCD camera. The laboratory version of this instrument (the Particle Phase Discriminator Mk2, PPD-2) has been used as a foundation of this work.

1.4 Overview of Thesis

The overall theme of this thesis is to explore methods in the measurement of forward light scattering patterns of individual fibrous aerosol particles in order to create a method of indirect measurement of the fibre morphology. This will help determine, following WHO guidelines, the respirability of the fibre and will hopefully fuel future instrument design. In summary, the first chapter has provided a reasoning behind the undertaking of this project. Chapter 2 reviews different mathematical light scattering models to find a suitable method to investigate the nature of how light scatters from fibres. Chapter 3 investigates the light scattered from different

fibrous samples to help validate the chosen simulations of Chapter 2 and to highlight some possible problems that could occur regarding instrumentation design. Chapter 4 uses simulated light scattering, made to resemble results from an existing instrument, to explore differences in the scattered light, depending on the fibres morphology, optical properties, and orientation. Methods for measuring length, and diameter are developed and tested using a Monte Carlo-based method, fibre orientation is also explored but not tested. Chapter 5 uses the methods developed in the previous chapter for testing and validation using data collected from a series of aerosolisation experiments. Finally, Chapter 6 contains the overall conclusions of the project and possible future work on instrument design, based around the conclusions made.

1.5 Formalisms

1.5.1 Light Scattering Definitions

There are two different kinds of light scattering: elastic and inelastic. Light is scattered when photons interact with an object of a different optical medium. Inelastic scattering is where the energy level of the incident photon is different to that of the photon after the interaction. Examples of this include fluorescence and Raman scattering. Elastic scattering is where the energy level of the incident photon does not change after the interaction and is a combination of diffraction, refraction, and reflection. An illustration of these is shown in Figure 1.4.

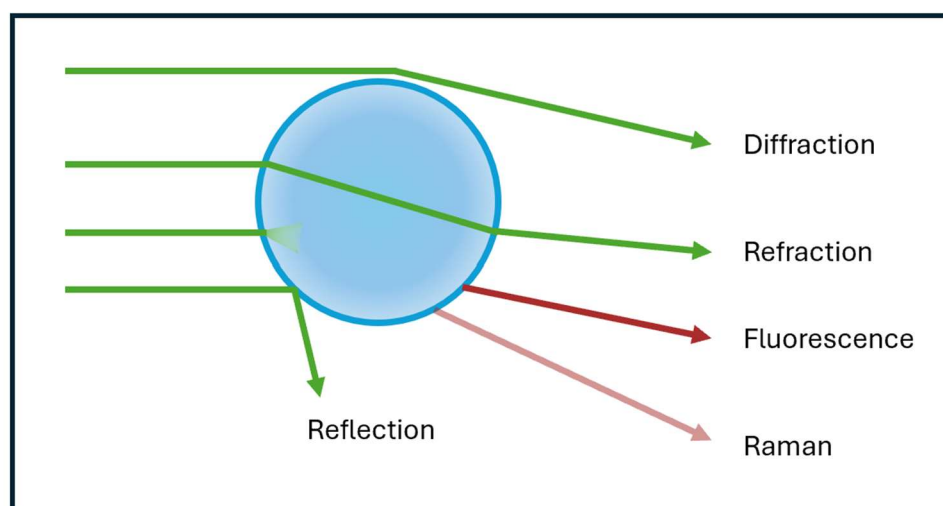


Figure 1.4: Illustration of different light scattering processes.

Throughout this project only elastic scattering will be considered and the combination of diffraction, reflection, and refraction will be referred to collectively as scattering.

1.5.2 Babinet's Principle

Babinet's principle states that the diffraction patterns produced by a 2D aperture are essentially identical⁸ to those produced by a 2D object of the same shape, i.e., complementary. A graphical explanation is shown in Figure 1.5, where the top left shows an example of a square aperture, the top right shows the complimentary shape of that aperture, and the bottom shows the approximated⁹ diffraction patterns produced by these images.

⁸ Polarisation will differ but irradiance will be the same

⁹ Using a Fourier transform of the image – further explanation in Appendix 7.1.

Graphical Explanation of Babinet's Principle

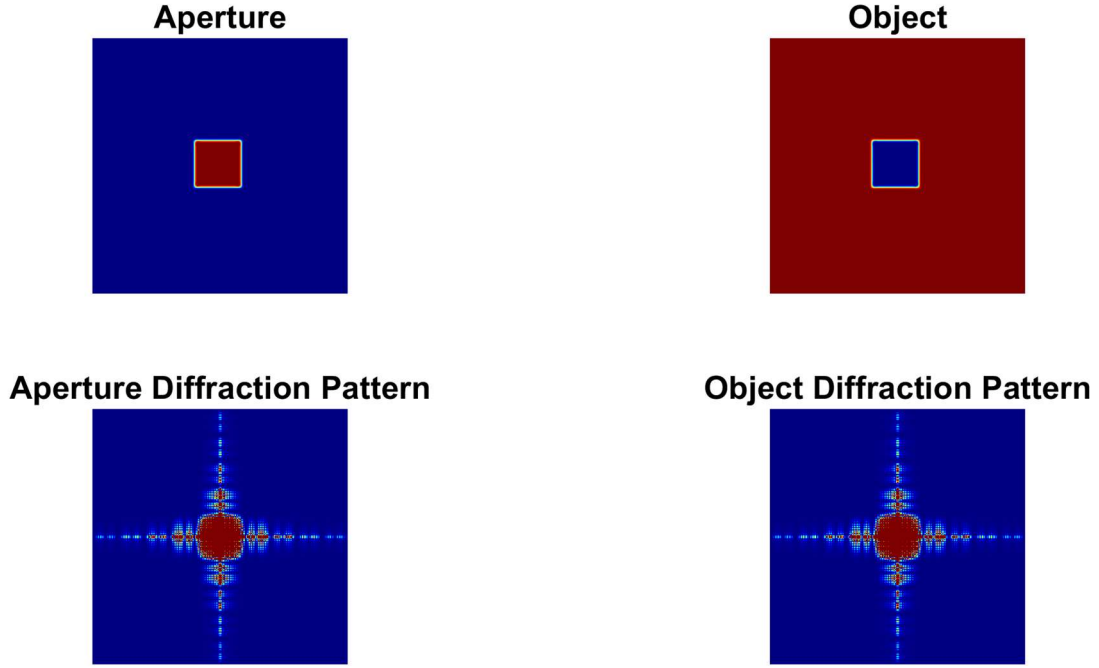


Figure 1.5: Graphical explanation of Babinet's principle; the top left shows a 2D square aperture and the top right shows the complimentary shape, below are the resulting diffraction patterns of both.

1.5.3 Maxwell's Equations

A collection of equations that describe the macroscopic relationship between the electric and magnetic fields for the interior points of matter were summarised by James Clerk Maxwell and are now known as Maxwell's Equations. Many different forms of these equations can be found in literature, however, Hecht (2017) give these set of equations as follows:

$$\oint_C \vec{E} \cdot d\vec{\ell} = - \iint_A \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$$

Equation 1.4

$$\oint_C \vec{B} \cdot d\vec{\ell} = \mu_0 \epsilon_0 \iint_A \frac{\partial \vec{E}}{\partial t} \cdot d\vec{S}$$

Equation 1.5

$$\oiint_A \vec{E} \cdot d\vec{S} = 0$$

Equation 1.6

$$\oiint_A \vec{B} \cdot d\vec{S} = 0$$

Equation 1.7

where $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, ϵ_0 is the permittivity of free space, μ_0 is the permeability of free space, C represents the closed curve in which the open area A is bound that

the magnetic field passes through, $\vec{\ell}$ is the vector along the curve C , and $\vec{S}$ is the vector that points outward perpendicular to the surface of A . These are simplified versions of the equations, assuming no free current or charge, i.e., the displacement current density $\vec{J}$ and the charge distribution density ρ are both zero.

Equation 1.4 is essentially Faraday's Law of Induction, it tells us that integral of the electric field $\vec{E}$ around the closed loop C gives the amount of magnetic field $\vec{B}$ perpendicular to the surface A . The loop C can be arbitrarily chosen and so the electric field is found due to the time-varying magnetic field. Equation 1.5 is essentially Ampère's Circuital Law, without the displacement current density, and shows that a time-varying electric field produces a magnetic field. These two equations highlight the interconnectedness of the electric and magnetic fields. Equation 1.6 and Equation 1.7 are essentially the electric and magnetic components of Gauss's Law respectively. The net flux of the electric field through the volume of the enclosed area A of Equation 1.6 is proportional to the enclosed charge, when the charge density is zero the net flux is also zero. The same enclosed area A of Equation 1.7, within a magnetic field, will have an equal number of field lines entering and egressing from it due to the absence of monopoles, hence the total magnetic flux through the enclosed area A is zero.

1.5.4 Stokes Vector & Mueller Matrix

To explain the Mueller matrix, a common output of light-simulation software that will be explored in Chapter 2, it is first necessary to explain the Stokes vector and its corresponding parameters, taken from Hecht (2017). The Stokes vector describes the polarisation state of light and can represent both polarised and partially polarised:

$$\mathbf{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle |E_x|^2 + |E_y|^2 \rangle \\ \langle |E_x|^2 - |E_y|^2 \rangle \\ \langle E_x^* E_y + E_x E_y^* \rangle \\ i \langle E_x E_y^* - E_x^* E_y \rangle \end{bmatrix}$$

where E is the amplitude of the electric field polarised in the x and y directions, indicated by their subscripts, and the superscript $*$ indicates the complex conjugate. The parameters I , Q , U , and V describe the intensity of the light and the degree of horizontal, diagonal, and circular polarisation respectively. A graphical representation is shown in Figure 1.6.

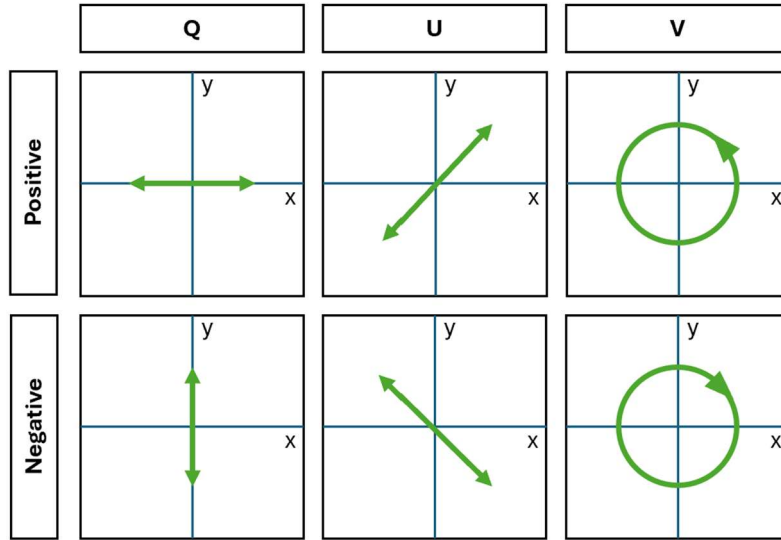


Figure 1.6: Graphical representation of the polarisation elements of a Stokes vector. The top row shows the polarisation of light for a positive value and the bottom row for negative. The direction of the polarisation is indicated by the green arrows.

The Mueller matrix can then be used to manipulate the Stokes vector, acting as an object of particular optical properties:

$$\mathbf{S}_t = \mathbf{M}\mathbf{S}_i$$

where the subscripts i and t represent the incident and transmitted light described by the Stokes vector respectively and the Mueller matrix is as follows:

$$\mathbf{M} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{34} & S_{44} \end{bmatrix}$$

Each element of $\mathbf{M}$ is a description of any change in the polarisation state of light and details of each element are described by Hovenier (1994). An example of how the Mueller matrix and Stokes vector are used is given below; unpolarised light, represented by the Stokes vector $\mathbf{S}_u$, interacting with a horizontal linear polariser, represented by the Mueller matrix $\mathbf{M}$, to produce the resultant Stokes vector $\mathbf{S}_r$:

$$\mathbf{M}\mathbf{S}_u = \mathbf{S}_r$$

$$\frac{1}{2} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

The resulting Stokes vector $\mathbf{S}_r$ shows that the irradiance is now $1/2$ and, as the Q component is positive, it is horizontally polarised.

For this investigation, only the element S_{11} will be used which describes the light intensity for each scattering angle of θ and φ that will be explained in Section 1.5.5.

1.5.5 Scattering Angles

The direction of the light scattered from an object will be described using the scattering angles θ and φ . The propagation direction of the incident light will be the datum for $\theta = 0^\circ$ and $\varphi = 0^\circ$ of the scattered light. Measurements taken in the zenithal and azimuthal components will be measured in angles of φ and θ respectively.

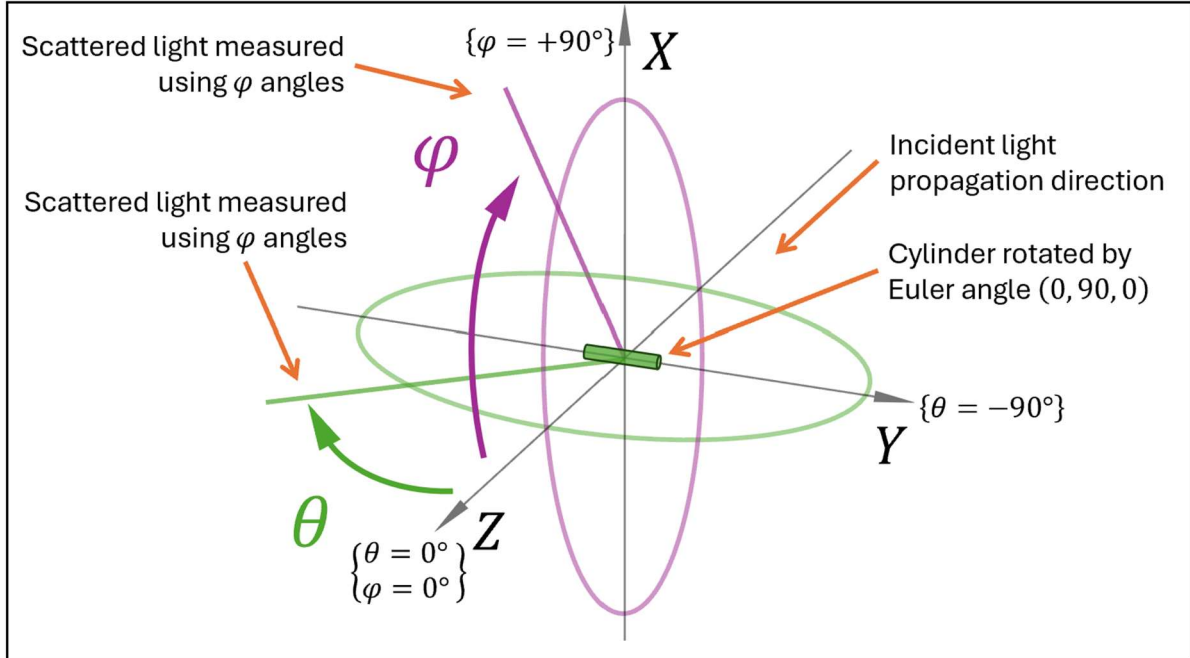


Figure 1.7: Graphical explanation of scattering angles θ and φ using a cylinder with its major axis perpendicular to the incident light propagation direction as an example.

Figure 1.7 shows an example of the angles θ and φ to describe the light scattered from a cylinder in the centre of a reference frame. The propagation direction of the incident light travels along the positive Z axis and is scattered by the cylinder, rotated using Euler angles that will be explained in Section 1.5.6.

This will be used as a reference to describe the scattering patterns throughout this investigation.

1.5.6 Euler Angles

To ensure greater clarity throughout this project, regarding the orientation of a fibre relative to the incident laser light, Euler angles will be used. The angles α , β , and γ are used to describe the orientation of a transformed reference axis (x, y, z) from its original orientation (X, Y, Z). The reason for its use is that it is a concise way of describing an objects orientation and it is also used to set the orientation of the scattering object in many light scattering models.

The reference coordinate system (X, Y, Z) is set by the incident light position, with the Z axis being the propagation direction of the incident light in the positive direction. For the models explored in Chapter 2, the fibre's major axis is also aligned along the Z axis and centred with the coordinate system, i.e., the propagation direction of the incident light is first aligned with the major axis of the fibre. Examples of this initial state are shown in Figure 1.8 and include the reference frame (left) a cylinder example (middle), and a 2D rectangle in the Z-Y plane (right) for a graphical explanation.

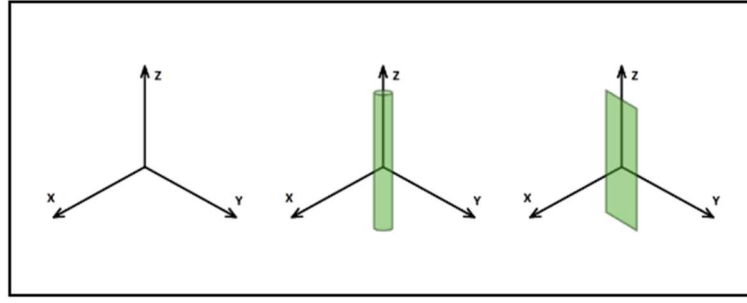


Figure 1.8: Reference frame for Euler angles explanation – Initial state, no rotation.

The first Euler angle α rotates the reference coordinate system about the Z axis, as shown in Figure 1.9, creating a new coordinate system (N, Y', Z) where the new X axis is called the line of nodes (N). So far, this transformation has only rotated the fibre about its major axis and so will not have changed if perfectly cylindrical and any scattering patterns made from a fibre in this orientation would resemble something like a droplet or sphere.

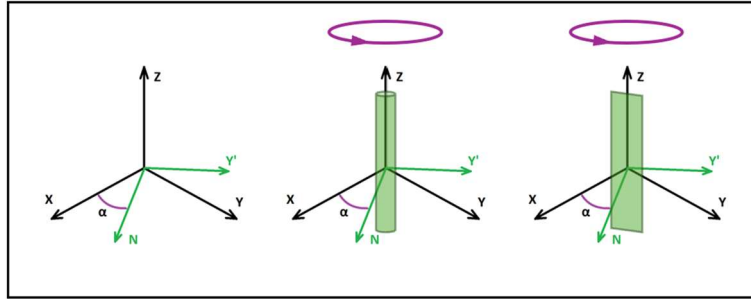


Figure 1.9: Reference frame for Euler angles explanation – Initial rotation about the Z axis by α° .

The second Euler angle β rotates the transformed coordinate system about the new line of nodes N , as shown in Figure 1.10, making a new coordinate system (N, Y'', z) . For example, a β rotation of 90° (0, 90, 0) would result in the fibre being aligned with the X - Y plane of the original coordinate system, i.e., perpendicular to the propagation direction of the incident light.

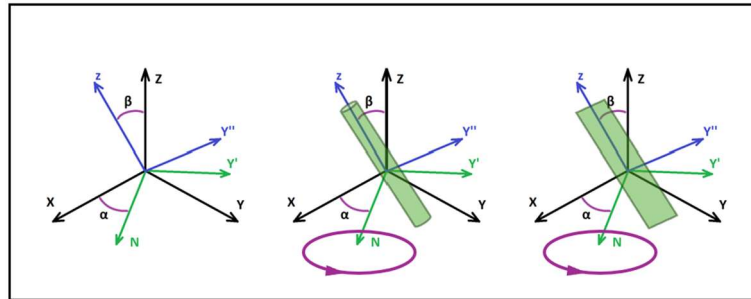


Figure 1.10: Reference frame for Euler angles explanation – Second rotation about the line of nodes (N) by β° .

Finally, shown in Figure 1.11, the third Euler angle γ rotates the transformed coordinate system about the new Z axis, creating the new coordinates (x, y, z) . The orientation of an object, relative to the orientation of the incident light, can now be made using the Euler angle transformation $(X, Y, Z) \rightarrow (\alpha, \beta, \gamma) \rightarrow (x, y, z)$.

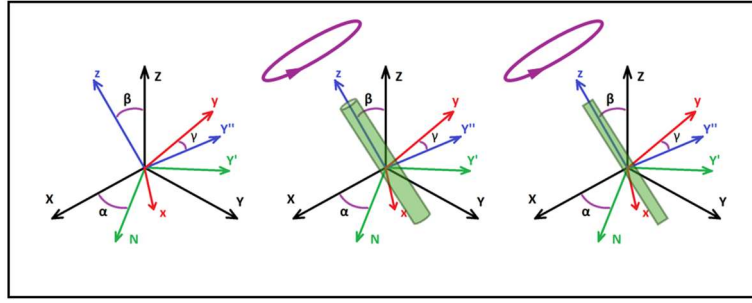


Figure 1.11: Reference frame for Euler angles explanation – Final rotation about the z axis by γ° .

For reference, all the simulated data will have the Euler angles $(0, 90, 0)$, unless otherwise stated, and so will create a symmetrical bright band aligned vertically. An example of this orientation is shown in Figure 1.12 (centre), the accompanying images are examples of scattering data of a fibre captured by PPD2 (left) and the modelled 90° forward scattering of a cylinder (right), both with the same orientation.

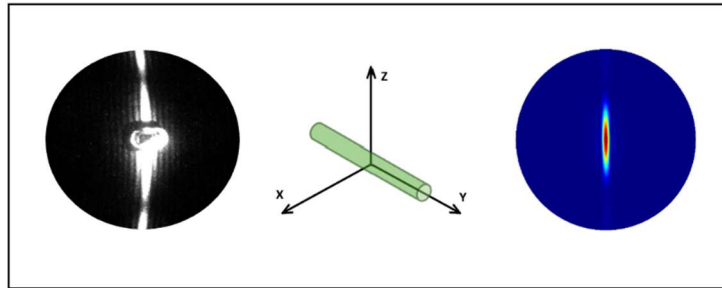


Figure 1.12: Example of a cylinder orientated at an Euler angle of $(0, 90, 0)$ (centre). The right image shows the modelled 90° forward scattering of a cylinder with the same orientation. The left image shows light scattering data captured by PPD2 of a fibre of similar orientation.

2 Simulations

*“So far gone am I in the dark side of the earth,
that its other side, the theoretical bright one,
seems but uncertain twilight to me.”
-Herman Melville, Moby Dick, 1851*

2.1 Introduction

The generation of a mono-disperse¹⁰, fibrous aerosol is an achievable but difficult task. The use of micromachined fibres was mentioned in the introduction, however, they were difficult to aerosolise, as discussed in Chapter 1. A supply of mono-disperse, fibrous aerosol would be invaluable for this project, providing a known input of diameter, length, and refractive index, to relate to a resultant scattering pattern captured by light scattering instrumentation, such as the Particle Phase Discriminator mk. 2 (PPD2). Because of the lack of availability of these ideal samples and the difficulty in their aerosolisation, an alternative method into the investigation of light scattering from fibres is necessary.

The alternative, wherein a known input is used to produce a light scattering pattern, is to model the scattered light using theoretical methods or light scattering simulations. Light scattering models are applied to provide insights into different investigations spanning many different disciplines. Examples include applications in biological fields (Asthagiri et al., 2005), atmospheric science (Nousiainen et al., 2011), analytical chemistry (Andersson et al., 2003), geology (Bänninger & Flühler, 2004), and many others.

This chapter investigates different light scattering models that could offer insights into the light scattered by a fibre. The models will start as simple as possible and progress into more complex systems.

2.2 Modelling with Diffraction Theory

2.2.1 Classical Diffraction Theory

2.2.1.1 Background

The far-field (Fraunhofer) interference patterns resulting from diffraction of light through a slit provide a simple approximation to that of a fibre. This technique has been previously used by Powers & Somerford (1978a), where a Fourier transform¹¹ of the scattering patterns produced by different sized slits and different diameter fibres were used to accurately measure the width. This method is essentially the same as the one described here and will be discussed in the next section. Unfortunately, they also stated this method's lack of ability to perform well with smaller sizes that coincide with the respirable diameter range. Nevertheless, aspects of this method are worth investigating for completeness.

2.2.1.2 Theory

The classical derivation of the single slit diffraction equation is relatively simple and can be achieved by approximating a wavefront as a series of oscillators. The equation describing the intensity distribution of light passing through a single, infinite slit is given by Hecht (2017):

¹⁰ As in uniform size and not concentration.

¹¹ Discussed in Section 2.2.2.

$$I(\theta) = A \left(\frac{\sin \beta}{\beta} \right)^2$$

Equation 2.1

where:

$$\beta = \frac{\pi d}{\lambda} \sin \theta$$

Equation 2.2

with I being the irradiance as a function of the angle θ , A is the amplitude of the light, d is the width of the slit, and λ is the wavelength of the incident light. A graphical representation of this is shown in Figure 2.1.

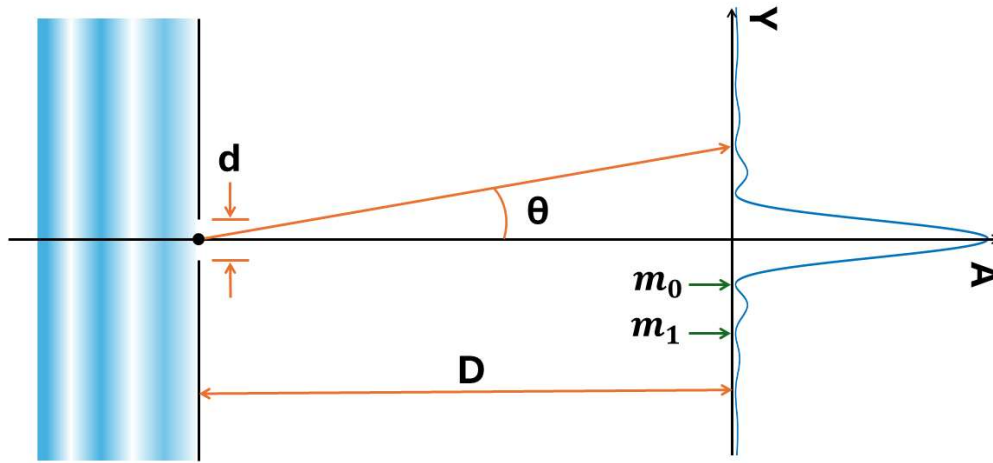


Figure 2.1: Graphical representation of single slit diffraction.

When the distance from the source to the screen is sufficiently large, i.e., in the Fraunhofer scattering region, the intensity of the diffraction pattern will look similar to the example in Figure 2.1 (right-hand side line). Scattered light measured at a closer distance will be in the Fresnel regime and appear very different to the example shown.

For values of $\beta = \pm\pi m$ ($m = 1, 2, 3, 4 \dots$), $\sin \beta = 0$ which correspond to angular locations where $I(\theta) = 0$, resulting in destructive interference. These are the locations of the pattern minima of order m as shown in Figure 2.1.

It is thus possible to calculate the width of the slit using the intensity minimum angular locations¹² when the wavelength is known:

$$d = \frac{m\lambda}{\sin \theta_m}$$

Equation 2.3

¹² The first of which ($m = 1$) referred to henceforth as the “minimum” – unless otherwise stated.

Where θ_m indicates the minimum point of order m .

From Babinet's principle (see Chapter 1), the width of a thin slit, analogous to a fibre object could be measured using the values found from the minimum points.

This is the first step to understanding how the light scattering from fibres might appear and a possible approach to measuring the diameter of those fibres. The next section shows some examples of the resultant interference patterns produced by single slit diffraction.

2.2.1.3 Example diffraction patterns

2.2.1.3.1 One-Dimensional Diffraction Patterns

By using the equations shown in the previous section, interference patterns can be generated. In order to provide some continuity, a wavelength of 532 nm will be used throughout this entire project – this is the wavelength of light of the laser used in PPD2.

Figure 2.2 shows the patterns produced by slit widths of 0.75 μm and 2.5 μm in blue and orange respectively.

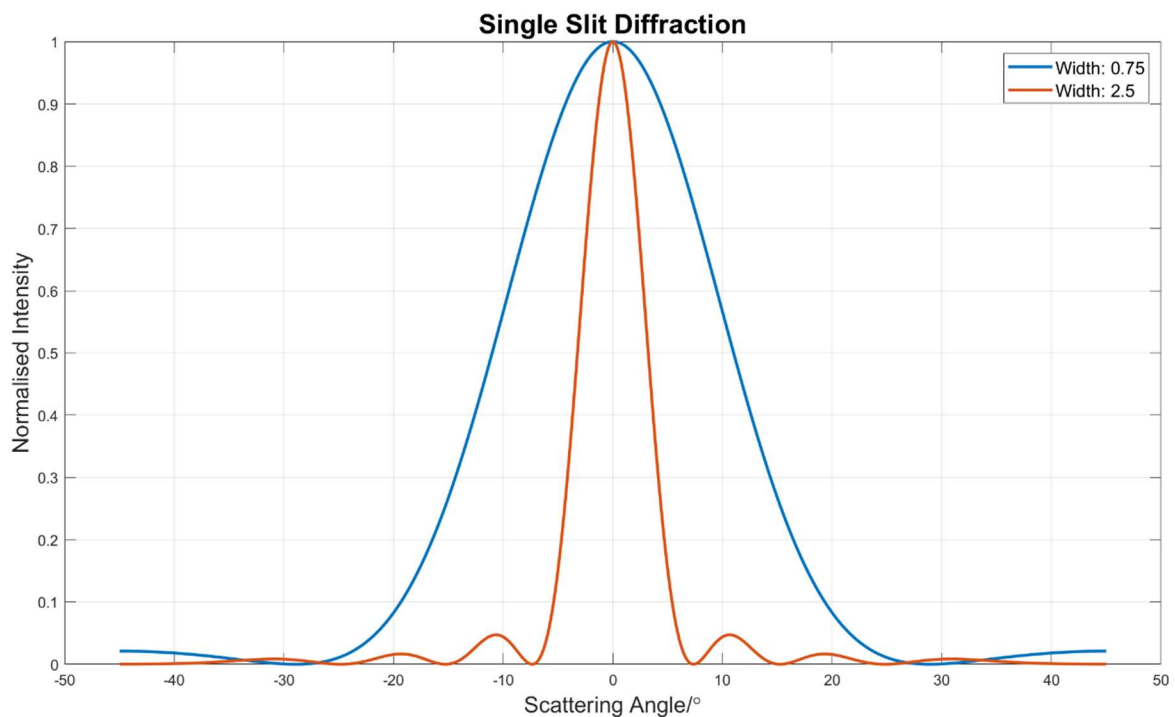


Figure 2.2: Resultant, normalised diffraction pattern from single slit interference of widths 0.75 μm (blue) and 2.5 μm (orange).

What can be seen from this is that as the slit increases in size, the angular positions of the minima decrease. The relationship between the first minimum (m_0) and the slit width is shown in Figure 2.3.

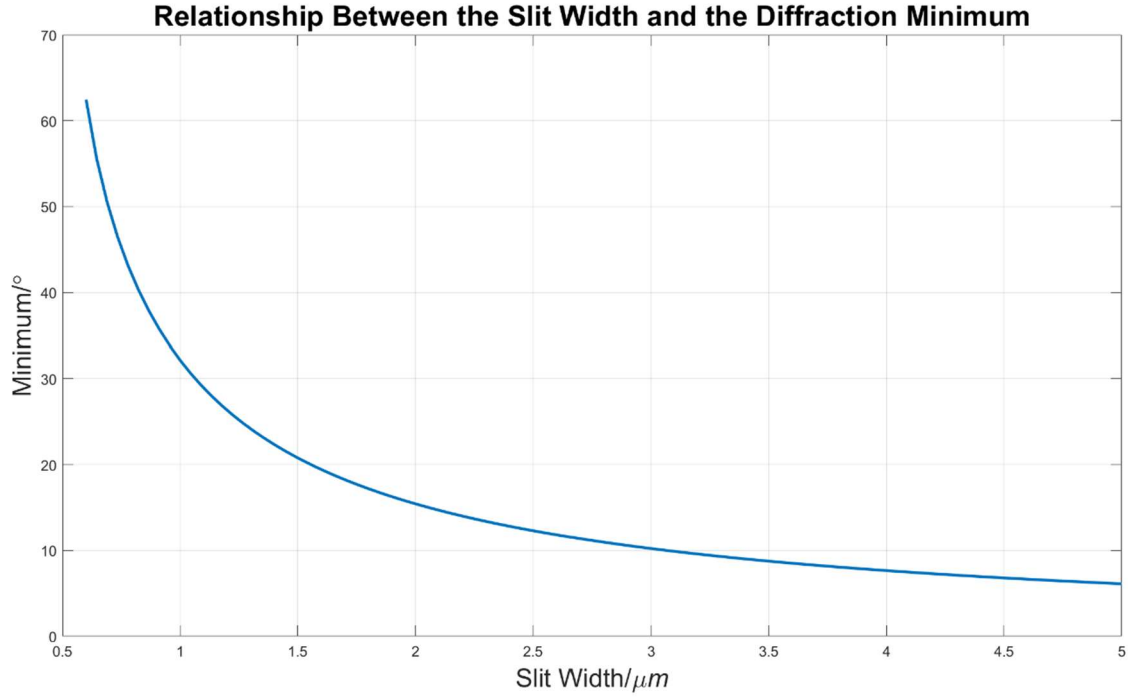


Figure 2.3: Graphical representation of the relationship between the first minimum of single slit diffraction patterns and the corresponding width of the slit.

This monotonic relationship may provide a reliable means of measurement.

2.2.1.3.2 Two-Dimensional Diffraction Patterns

The arrays found from the calculations of Equation 2.1, displayed in the previous section, can be used to create a 2D pattern from the vector outer product. If the values of the resulting interference patterns are represented as the vectors:

$$\tilde{A} = A_1, A_2, A_3, \dots A_n \text{ \& } \tilde{B} = B_1, B_2, B_3, \dots B_n$$

where the vectors $\tilde{A}$ and $\tilde{B}$ represent the data of two different diffraction patterns such as the blue and orange lines of Figure 2.2. Then the 2D scattering pattern M is the vector outer product of $\tilde{A}$ and $\tilde{B}$:

$$M = \tilde{A} \otimes \tilde{B} = \begin{pmatrix} A_1 B_1 & \cdots & A_n B_1 \\ \vdots & \ddots & \vdots \\ A_1 B_n & \cdots & A_n B_n \end{pmatrix}$$

Figure 2.4 shows the results of applying this vector outer product to the two different vectors found from the two different diffraction results from Equation 2.1.

**Vector Outer Product of Two Single Slit Diffraction Patterns
of Widths $0.75\ \mu\text{m}$ and $2.5\ \mu\text{m}$ for $\lambda = 532\ \text{nm}$**

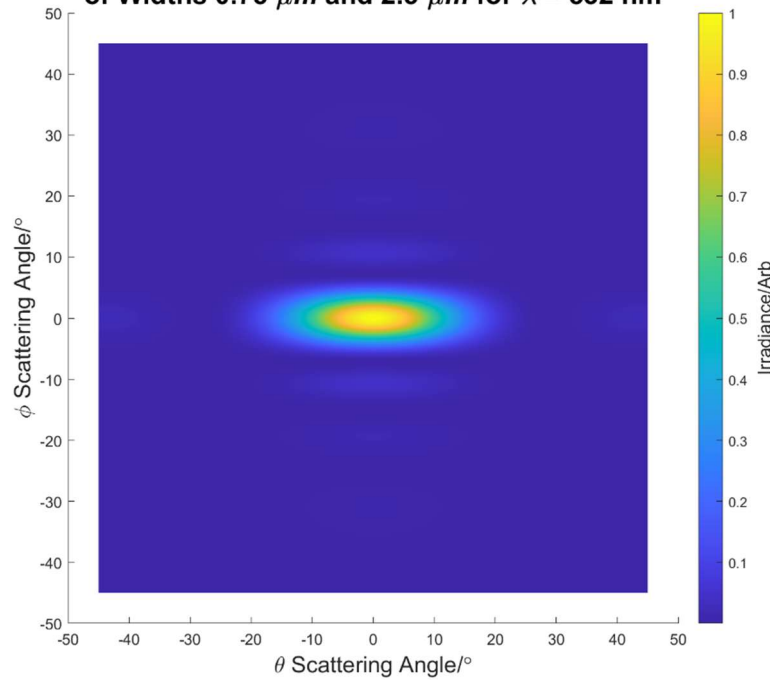


Figure 2.4: The vector outer product of two single slit diffraction patterns of widths $0.75\ \mu\text{m}$ and $2.5\ \mu\text{m}$.

The interference pattern shown in Figure 2.4 resembles the scattered light shown in the crocidolite examples of Figure 1.3; a bright central band of light. The crocidolite samples showed a much thinner and longer band, however, this is the start of some understanding into the light scattered from respirable fibres.

2.2.1.4 Limitations

Although this model is simple, it may be too simple to be representative enough for the light scattered from fibres. The lack of consideration into a materials' refractive index may be adequate for highly absorbing materials, as they will show a greater amount of diffraction. However, more transparent materials will most likely produce a scattering pattern that is very dissimilar. This model only considers diffraction, the other elastic scattering effects – reflection and refraction – are not considered.

The assumption that the scattering produced by the length and diameter of a fibre or cylinder are independent of each other could be wrong. The vector cross product of two separately generated scattering patterns (shown in Figure 2.4) may then not be a viable representation of the expected scattering. Additionally, all of these rely on an incident light that is normal to the object, i.e., there is no orientation in a third dimension considered. The effect of orientation of the object on the resulting scattering pattern will be explored in Chapter 4.

2.2.2 Fourier Optics Model of Diffraction

2.2.2.1 Background

Similar to the work by Powers & Somerford (1978a), mentioned in Section 2.2.1.1, the inverse of what they did can be used to generate the diffraction pattern of an object or aperture by applying a Fourier transform to the scattering pattern. Powers & Somerford (1978b) took the Fourier transforms of scattered light to approximate the size of the object that caused the

scattering, the Fourier transform of the object will produce the diffraction pattern. The results in this section are expected to be very similar to those of the Section 2.2.1.

2.2.2.2 Theory

An object or slit in one dimension can be represented by a square pulse spatial function, $h(x)$. The square pulse function will equal some amplitude A when x is between $\pm L_0$, making the width of the square pulse $2L_0$.

$$h(x) = \begin{cases} A, & -L_0 \leq x \leq L_0 \\ 0, & \text{otherwise} \end{cases}$$

The Fourier transform of h would then be:

$$\mathfrak{F}(h) = \int_{-\infty}^{\infty} h(x) \exp(-j2\pi fx) dx$$

where $j = \sqrt{-1}$ and f is the spatial frequency. Euler's formula can then be used to replace the exponential function:

$$\begin{aligned} \exp(j\varphi) &= \cos(\varphi) + j \sin(\varphi) \\ \mathfrak{F}(h) &= \int_{-\infty}^{\infty} h(x) [\cos(2\pi fx) - j \sin(2\pi fx)] dx \end{aligned}$$

As the $\sin$ of any multiple of π will be zero, integrating, replacing h , and setting the limits to the square pulse width gives:

$$\mathfrak{F}(h) = A \left[\frac{1}{2\pi f} \sin(2\pi fx) \right]_{-L_0}^{L_0}$$

Finally arriving at the expression:

$$\mathfrak{F}(h) = \frac{A}{\pi f} \sin(2\pi f L_0)$$

Equation 2.4

This can also be extended into a second dimension by the addition of a y -axis to make a rectangular function:

$$h(x, y) = \begin{cases} A, & -L_x \leq x \leq L_x \\ A, & -L_y \leq y \leq L_y \\ 0, & \text{otherwise} \end{cases}$$

Taking the Fourier transform of h :

$$\mathfrak{F}(h) = \iint_{-\infty}^{\infty} h(x, y) \exp(-j2\pi[f_x x + f_y y]) dx dy$$

The exponential function can be separated using the rule:

$$\exp(A + B) = \exp(A) \exp(B)$$

And solving in the same manner as previously shown the equation becomes:

$$\mathfrak{F}(h) = \left(\frac{A}{\pi}\right)^2 \left(\frac{1}{f_y f_x}\right) \sin(2\pi f_x L_x) \sin(2\pi f_y L_y)$$

Equation 2.5

Unfortunately, these results have the units of inverse length, i.e., spatial frequency, and are not completely representative of a physical system in their current state. The reason behind these strange units is how the Fourier transform is the decomposition of the function in terms of its spatial frequencies and only a representation of the physical system. A more in-depth explanation is given in Appendix 7.1.

2.2.2.3 Application

2.2.2.3.1 One-Dimensional

Using Equation 2.4 and setting the value for L_0 to produce a width the same as the examples of the previous section ($0.75 \mu\text{m}$ and $2.5 \mu\text{m}$) produces the plot shown in Figure 2.5.

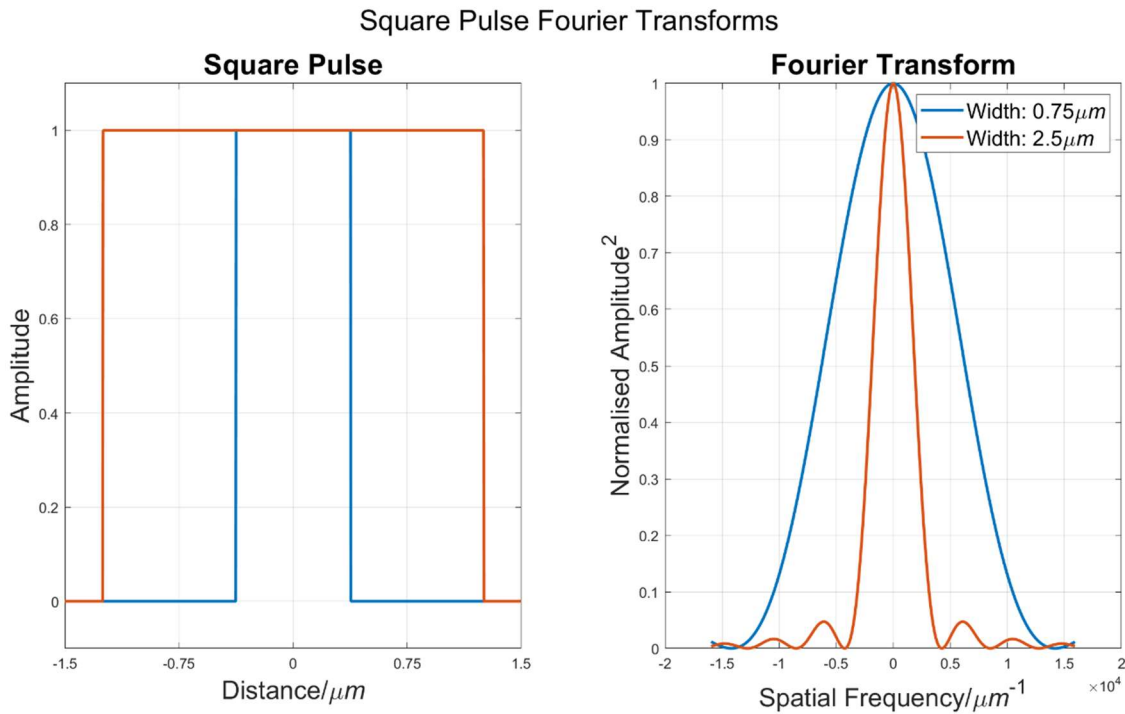


Figure 2.5: Square pulses (left) plotted as representations of a one-dimensional object or slit and their resultant Fourier transforms (right) for pulse sized of $0.75 \mu\text{m}$ and $2.5 \mu\text{m}$.

2.2.2.3.2 Two-Dimensional

Using Equation 2.5, found from the Fourier transform of a rectangular pulse and using the same inputs from the previous example, a $0.75 \mu\text{m} \times 2.5 \mu\text{m}$ rectangular pulse and the resulting diffraction pattern is shown in Figure 2.6.

Rectangular Pulse Fourier Transforms

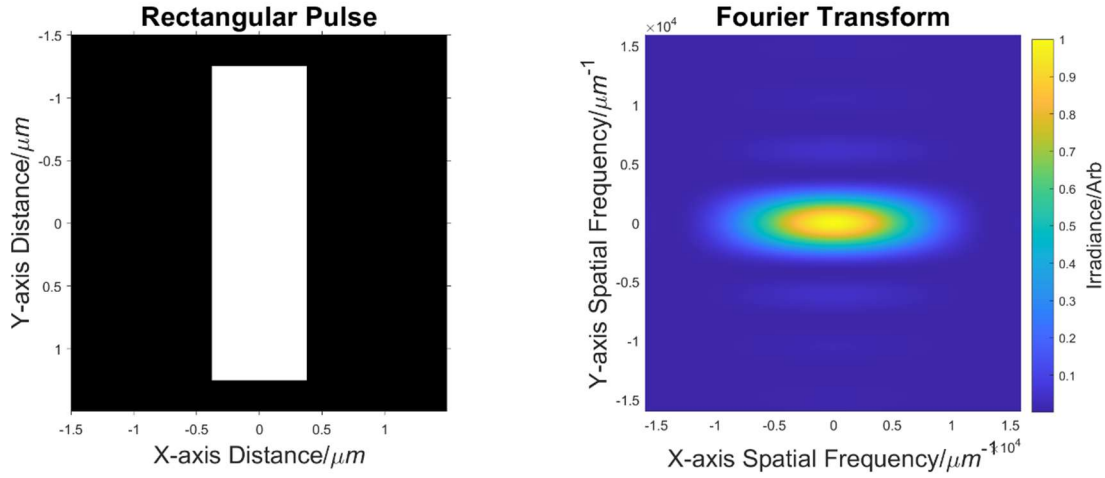


Figure 2.6: A rectangular pulse (left) of dimensions $0.75 \mu\text{m}$ by $2.5 \mu\text{m}$ and the resultant two-dimensional Fourier transform (right).

Again, this result shows resemblance to the modelled scattering patterns shown previously and a good match with the results shown in Figure 2.4.

2.2.2.4 Limitations

The limitations that are noticed in this model are the same of those discussed in Section 2.2.1.4. Additionally, to make the model more representative a conversion factor needs to be included, resulting in a measurable interference pattern and the incorporation of a wavelength. Before this conversion factor is used the results are very abstract as the resulting diffraction pattern found is given as an inverse length.

2.3 Lorenz-Mie Theory

2.3.1 Background

In 1908 Gustav Mie published his work describing the electromagnetic interaction between a homogeneous sphere and an incident plane wave (Mie, 1908). However, as mentioned by Gouesbet (2008), Ludvig Lorenz had described an empirically equivalent model prior to Mie's publication. Lorenz's model, interestingly, was based on a very different mechanism. The main reasons that this model is being considered is that it is numerically exact and requires little computer processing to generate scattering patterns.

2.3.2 Theory

2.3.2.1 Basics

A derivation of the Lorenz-Mie theory scattering from a sphere is beyond the scope of this project, however, it is demonstrated in Bohren & Huffman (1998). Essentially, solutions to Maxwell's vector wave equations of electromagnetism are solved using spherical-polar coordinates. By incorporating additional considerations into this model, a further set of models, commonly known as Generalised Lorenz-Mie Theories (GLMTs), have been created. These considerations include the use of arbitrarily shaped beams instead of plane waves, such as Gaussian to emulate laser light, as discussed by Ambrosio et al. (2024).

2.3.2.2 Generalised Lorenz-Mie Theory for Infinite Cylinders

To extend this theory to be applicable to cylinders, albeit infinitely long, a similar derivation can be made, also demonstrated by Bohren & Huffman (1998). In this case, cylindrical-polar coordinates are used to solve Maxwell's vector wave equations of electromagnetism instead of spherical-polar coordinates. These are done in such a way that a solution can also be found for incident light that is at an oblique angle, i.e., the incident light is not perpendicular to the major axis of the cylinder. Additionally, Gouesbet et al. (1999) derived another GLMT for infinite fibres with an elliptical cross-section.

2.3.2.3 Finite Cylinders

Methods are also discussed in Bohren & Huffman (1998) that show different ways of approximating the scattering from a cylinder of finite length. The first method is the diffraction approximation. This method is based on the fact that a screen, or corresponding aperture of the same shape, and a 3D object of the same projected cross-sectional area will all scatter light in a similar way. A half-length measurement is then included in the calculations.

With the application of a vector outer product, described in Section 2.2.1.3.2, an even looser approximation can be made. Results of the Mie scattering for diameter can be combined with the diffraction results of an object corresponding to the desired length of the cylinder. An example of this is shown in Figure 2.8 in the next section.

Alternatively, the Rayleigh-Gans approximation can be used. Usually, this approximation is for particles that have a refractive index close to the surrounding medium, i.e., optically soft. However, the Rayleigh-Gans approximation is still valid for use with particles of arbitrary shape, such as finite cylinders.

These approximations discussed by Bohren & Huffman (1998) have not been included in the evaluation of the different scattering models due to time constraints. More representative light scattering models have been developed since these approximations and there would be inadequate available time to manually program these models. If any are available, they are not easily found.

2.3.3 Application

With the use of the MatLab (The MathWorks, Inc. ver. R2024a) software MatScat (Bohren & Huffman, 1998; J. Schäfer et al., 2012; J. P. Schäfer, 2011) the scattered light from an infinitely long cylinder can be quickly calculated. The sizes used as examples previously will be used again but as diameters rather than widths. Two refractive indices will be used, one of low absorption ($1.5+5e-6i$) and one relatively high ($1.5+0.5i$), to demonstrate the difference in the resulting scattering pattern. The plots, shown in Figure 2.7, are displayed on a logarithmic scale for the y-axis because of the high dynamic range of the resulting light amplitude. The amplitudes have also been normalised, i.e., divided by their maximum value, for the comparison of the different cylinder diameters.

Infinite Cylinder Mie Scattering

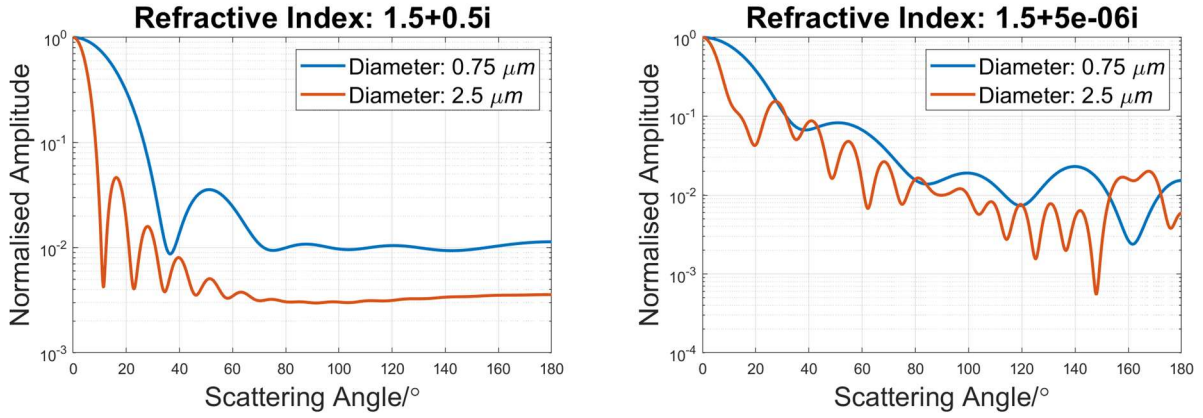


Figure 2.7: Scattering patterns generated using Mie theory for infinitely long cylinders of diameters $0.75 \mu\text{m}$ and $2.5 \mu\text{m}$. The left shows the results from a cylinder of refractive index $1.5+0.5i$ and the right $1.5+5e-6i$.

The results shown in Figure 2.7 from the higher refractive (left) index show a striking resemblance to the results of Section 2.2, however, when cylinder of greater transparency is used, the shape of the graphs show a noticeable difference.

As mentioned previously, the vector outer product may be used as a rough approximation for a finite cylinder. Combining the Mie scattering results of an infinitely long cylinder of diameter $0.75 \mu\text{m}$ and the diffraction pattern of a slit of width $10 \mu\text{m}$ produces the patterns shown in Figure 2.8. The left shows the results from a cylinder of refractive index $1.5+0.5i$ and the right $1.5+5e-6i$.

Vector Outer Product of a $0.75 \mu\text{m}$ Cylinder and a $10 \mu\text{m}$ Slit

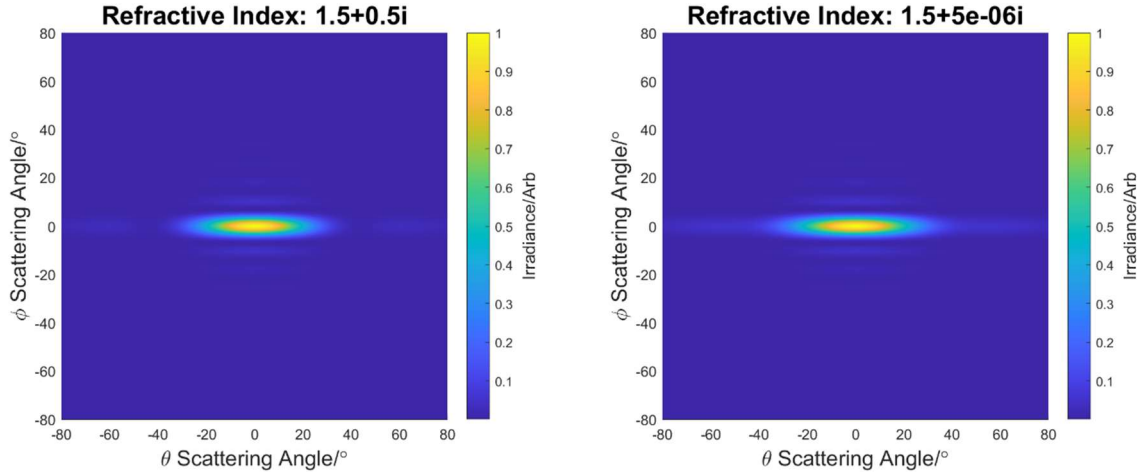


Figure 2.8: The vector outer products of an infinitely long $0.75 \mu\text{m}$ diameter cylinder and a $10 \mu\text{m}$ wide slit to approximate the scattering from a finitely long cylinder of refractive indices $1.5+0.5i$ (left) and $1.5+5e-6i$ (right).

A slight difference can be seen between the two images of Figure 2.8 at around $\pm 30^\circ$ of the θ scattering angle due to the internal reflective and refractive effects, in addition to the diffractive effects. See the blue lines in Figure 2.7 for the scattering at $\varphi = 0$.

2.3.4 Limitations

The GLMT may prove useful for modelling fibres with a view to creating a method to determine diameter and is computationally inexpensive. It also can account for changes in fibre orientation in principle, but it does not produce the curved scattering patterns which would be expected. Further investigation is required.

Approximations can be made to include the effects of length, with adaptations to the model for a finite cylinder. Unfortunately, the approximations described would require extensive programming to be applied to the current model. By using the vector outer product of the Mie scattering and diffraction to make a rough approximation of a finite cylinder does show a difference in the resultant pattern when using a different refractive index. How representative these results are to real life examples and other models is unknown and will be explored in future sections.

2.4 T-Matrix

2.4.1 Overview

Initially developed by Waterman (1965, 1969, 1971) and more recently updated by Waterman (2007), the T-Matrix method is so named from the linear relationship that can be approximated between the coefficients of the incident and scattered field, for Maxwell's equations, given by a transition matrix (Eremina & Wriedt, 2003). Multiplication of the incident light field vector with the T-Matrix results in the scattered light field vector (Asadova et al., 2024), and so benefits from being independent of the direction of the incident and scattered light. In other words, once the T-Matrix for a given object of a particular size, shape, refractive index, and orientation with respect to the coordinate system has been calculated, the resultant scattering field can be easily found for any incident light direction. Not only is the T-Matrix method applicable to the current work, but it can also be used to model other light scattering applications such as optical tweezers (Nieminen et al., 2011), or used for meteorological investigations (H. Li et al., 2024).

2.4.2 Application

An example of T-Matrix scattering software, Superellipsoid Scattering Tool (SScaTT), developed by Thomas Wriedt and Pablo García González (Doicu & Adrian, 2000; Wriedt, 2002) is shown here. The SScaTT program is executed from a graphical user interface (GUI) and has minimal input fields. The parameters of a superellipsoid can be altered for the following shape equation:

$$\left[\left(\frac{x}{a} \right)^{\frac{2}{e}} + \left(\frac{y}{b} \right)^{\frac{2}{e}} \right]^{\frac{e}{n}} + \left(\frac{z}{c} \right)^{\frac{2}{n}} - 1 = 0$$

For the parameters a , b , c , e , and n . An example of the superellipsoid shape generation of the SScaTT software is shown in Figure 2.9. Additionally, custom object files can also be read to be used for the calculations.

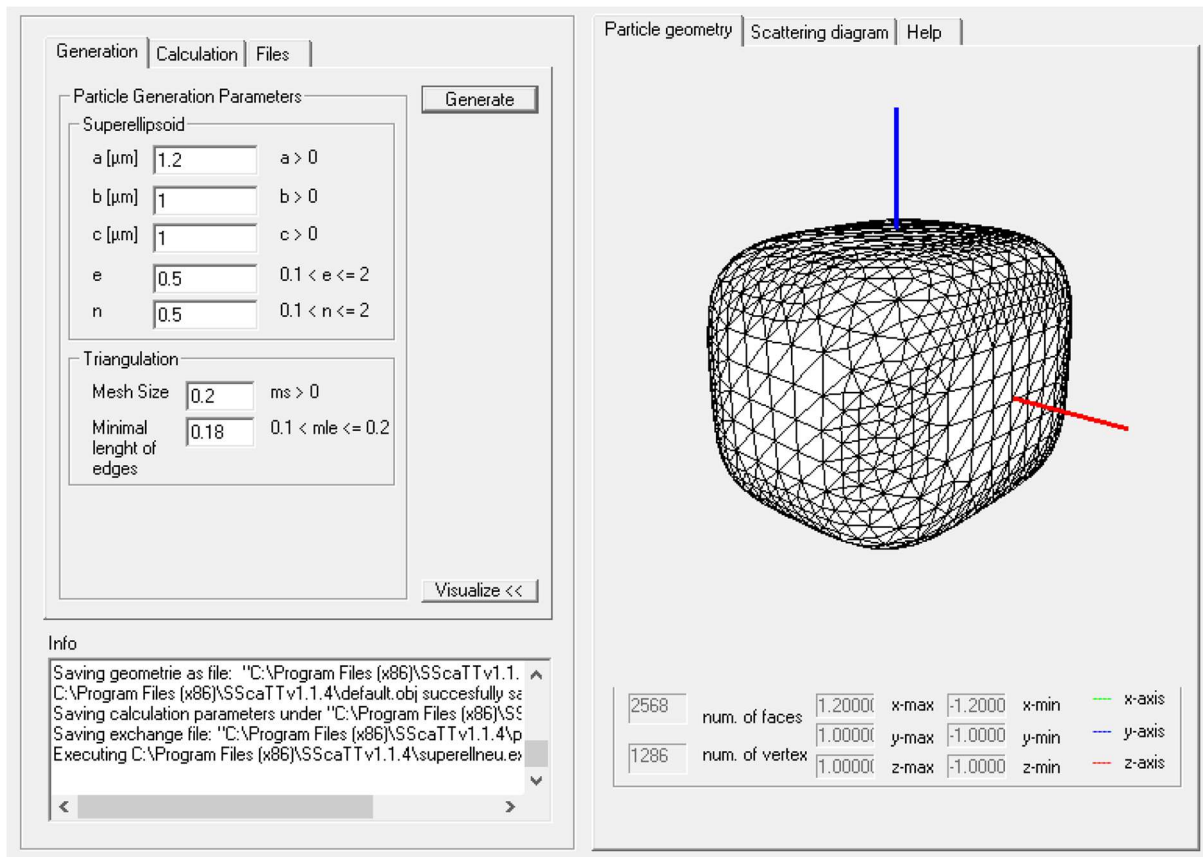


Figure 2.9: Screenshot of the SScaTT software showing the particle generation procedure for a superellipsoid of a 1.2 aspect ratio.

After generating the object, the light scattering can be generated using the T-Matrix method, shown in Figure 2.10.

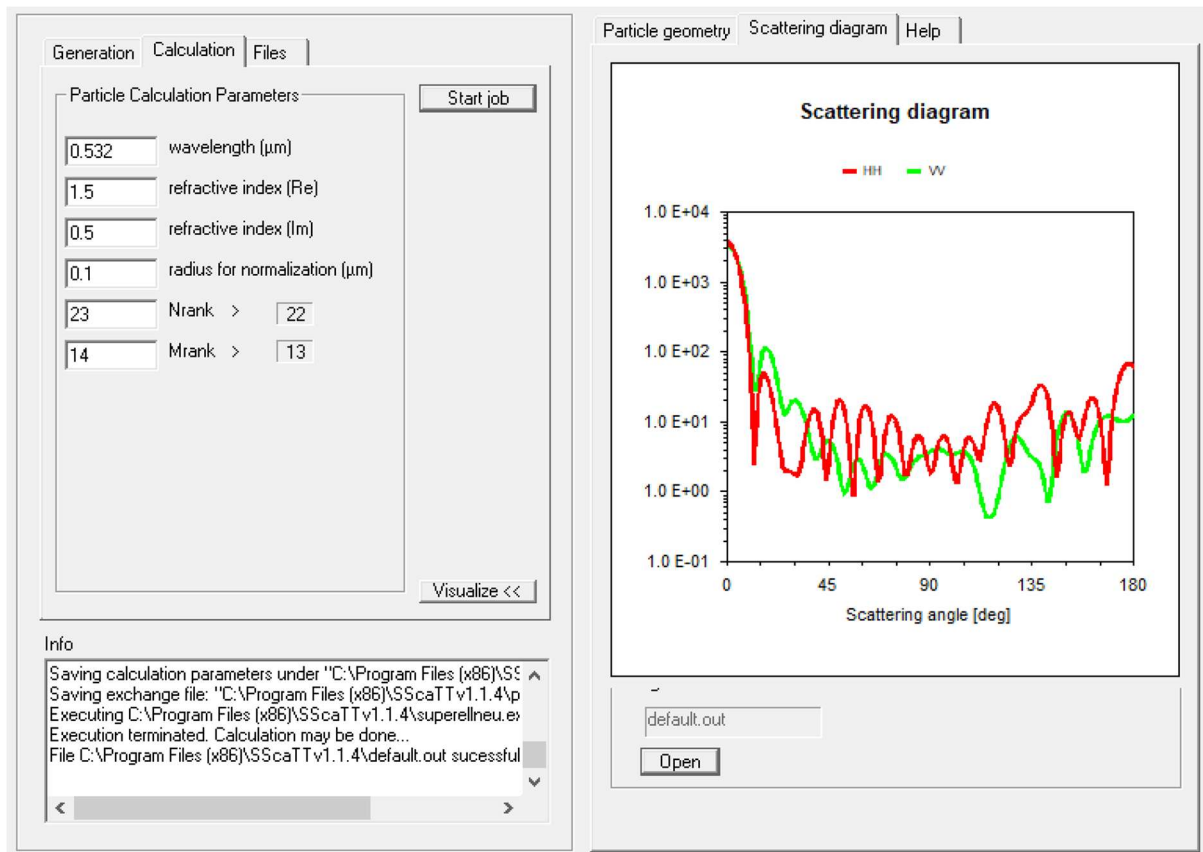


Figure 2.10: Screenshot of the SScaTT software with the T-Matrix scattering results of the object shown in Figure 2.9.

Unfortunately, the output is slightly confusing. The recommended supporting documentation is not a user guide for the software, but simply a single page containing a brief explanation, and so many other things are unexplained such as the HH and VV labels of the plot axes. The output file also contains HV and VH and, after inquiring about the meaning of these, H refers to the horizontal polarisation and V refers to the vertical polarisation, with VH and HV being the cross polarisation. Additionally, the M_{rank} and N_{rank} parameters, described by Doicu et al. (2019) as the maximum expansion order and number of azimuthal modes respectively, are also unexplained with only instructions in that they have to be larger than the value shown next to the input box. These terms are associated with linear algebra and the method used to solve Maxwell's equations and generate the resulting scattering, making the software confusing to someone who is unfamiliar. Finally, attempts at saving the scattering files from the software were fruitless and so no comparison to other models could be made.

An updated version of this model has been written in Fortran by Schmidt et al. (2009). It contains fewer restrictions than the one shown here, however has no GUI and the time investment required to master the software is not considered justified since alternative approaches exist.

2.4.3 Limitations

When considering the light scattering from fibres, the T-Matrix is restricted to objects with a maximum aspect ratio of around 20 (Eremina & Wriedt, 2003). The example shown in the previous section has a suggested upper aspect ratio limit of only four, stated in the help documentation, further limiting this models' use within this project. This would imply that at a diameter of 3 μm, the upper limit of the WHO size regulations, a length of around 6.7 μm would

be the largest fibre this model could accommodate. Waterman (2007) has revisited this model, however, to now include much higher aspect ratios.

Additionally, the availability of suitable software must also be considered. Many different T-Matrix programs are accessible, however, locating a version of the program made to accommodate the requirements of this work proved difficult. Most importantly, the requirement of accommodating objects with high aspect ratios, as most available code only dealt with spherical objects.

2.5 Discrete Dipole Approximation

2.5.1 Overview

The Discrete Dipole Approximation (DDA) was originally developed by Purcell & Pennypacker (1973) as a method of investigating the light scattered from arbitrarily shaped objects from wavelengths comparable the size of the object. It has since been adapted into many different light-scattering software, some of which are outlined by Chaumet (2022). The scattering objects used within this model are constructed from a three-dimensional matrix of elements that act as a discrete set of oscillators. The fields of the incident light and those of each oscillator are used to iteratively solve Maxwell's equations to determine the resulting scattering.

The application of DDA traverses a range of disciplines including astrophysics (Draine, 1988), biology (Gilev et al., 2010), microscopy (T. Zhang et al., 2013), and used to model light scattering mechanisms like optical tweezers (Chaumet et al., 2002). This can be achieved through a variety of different DDA programs, the most well-known of which are discussed by Chaumet (2022). These well-known DDA programs were investigated for the current project and assessed for several factors: ability to handle high aspect ratios, ease of use and access, method of implementation, reliability, and support. Of all these factors the Amsterdam Discrete Dipole Approximation (ADDA), developed by Yurkin & Hoekstra (2011), proved the best choice. No mention of high aspect ratio was found, however, it has been successfully tested for a size parameter¹³ of 320. The program can be executed using simple command-line inputs, explained by Yurkin & Hoekstra (2020), and runs on a Linux system which is important for its use on the University of Hertfordshire High-Performance Computer (UHHPC). The ADDA code is freely available on GitHub and actively supported, there is also a mailing list for troubleshooting and queries.

2.5.2 Example Models

Figure 2.11 shows two examples of the scattering results from cylinders using the ADDA software, using the same size and refractive indices as those in Sections 2.2 and 2.3 – 0.75 μm diameter with a 10 μm length, left shows an imaginary refractive index of 0.5 and the right 5e-6. The results are given in the form of a table of elements of the Mueller matrix at the corresponding angular coordinates. Both θ and φ are used, the azimuthal and zenithal scattering angles relative to the propagation direction of the incident light respectively, as explained in Chapter 1. The information needs extracting and organising into a two-dimensional matrix. Throughout this work the S_{11} element of the Mueller matrix will be used.

¹³ A ratio of the characteristic size (e.g. diameter) of a particle and the wavelength of the incident radiation.

ADDA Scattering Results from $0.75 \mu m \times 10 \mu m$ Cylinders

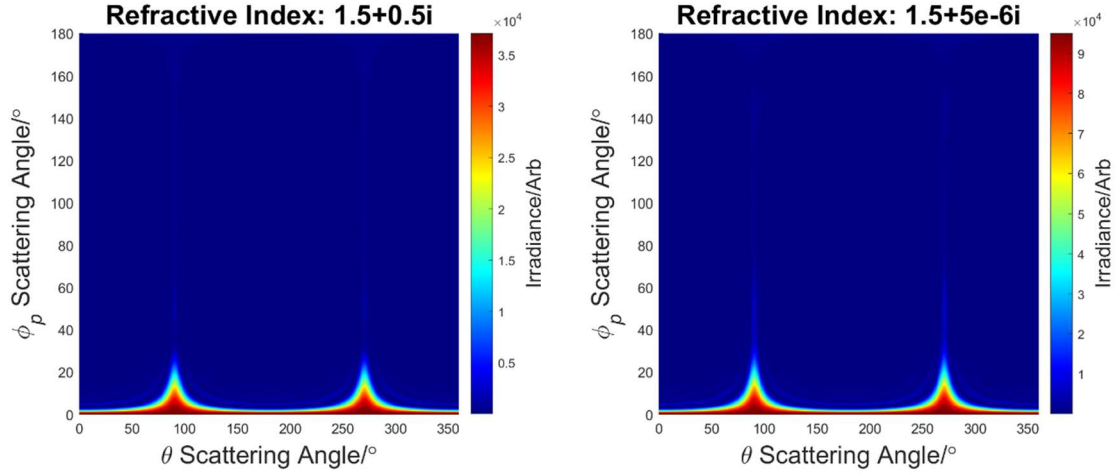


Figure 2.11: Results of the S_{11} scattering of the Mueller matrix generated by ADDA for $0.75 \mu m$ diameter and $10 \mu m$ long cylinders. The right shows the results of the cylinder of refractive index $1.5+0.5i$, the left $1.5+5e-6i$. This is how the data is given by ADDA, after some rearranging.

Initially the result of a scattering sphere is given as a square matrix, the y-axis representing the φ_p scattering angle in polar coordinates and the x-axis the θ scattering angle, each cell of the matrix contains the intensity for that corresponding angle. The data needed to be transformed into a polar coordinate frame to display the scattering data correctly, transforming the square net of the images in Figure 2.11 to a spherical surface, where the top and bottom horizontal lines (an angle of 0° and 180° of φ_p) map to a single point. Unfortunately, MatLab has no feature to plot an image in polar coordinates, only lines, so an alternative method in plotting was made (see Appendix 7.4.1). Consequently, the polar φ_p angle shown in Figure 2.11 is not the same as the φ angle explained in Section 1.5.5 and is only used here to explain the Mueller matrix output. Figure 2.12 shows the data displayed in Figure 2.11 but transformed to represent the forward (first 90° of the φ scattering angle) and back ($90^\circ - 180^\circ$ of the φ scattering angle) light scattering data from $0.75 \mu m$ diameter and $10 \mu m$ long cylinders of refractive index $1.5+0.5i$ (left) and $1.5+5e-6i$ (right).

ADDA Scattering Results from $0.75 \mu m \times 10 \mu m$ Cylinders

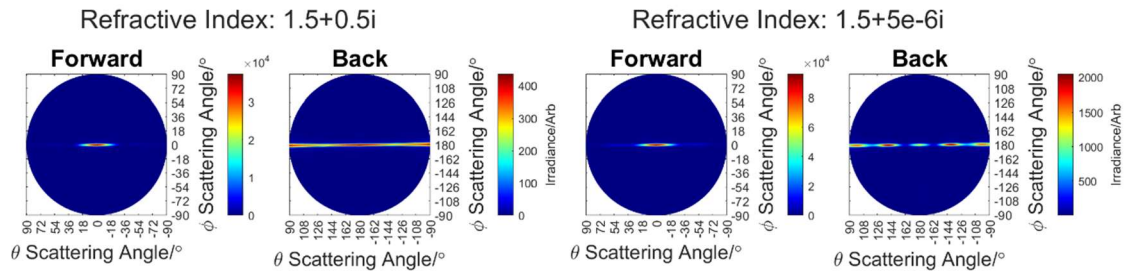


Figure 2.12: ADDA scattering results of the forward (first 90° of the φ scattering angle) and back ($90^\circ - 180^\circ$ of the φ scattering angle) light scattering from $0.75 \mu m$ diameter and $10 \mu m$ long cylinders of refractive index $1.5+0.5i$ (left) and $1.5+5e-6i$ (right).

Figure 2.13 (left) shows the scattering sphere, where the propagation direction of the incident light travels along the positive z-axis and is included to help visualise a connection between the 2D scattering patterns, such as those shown in Figure 2.13 (right) and the light scattered in a 3D space. The scattering object is located at the origin point (0, 0), however, this location is arbitrary as the object is illuminated by a plane wave.

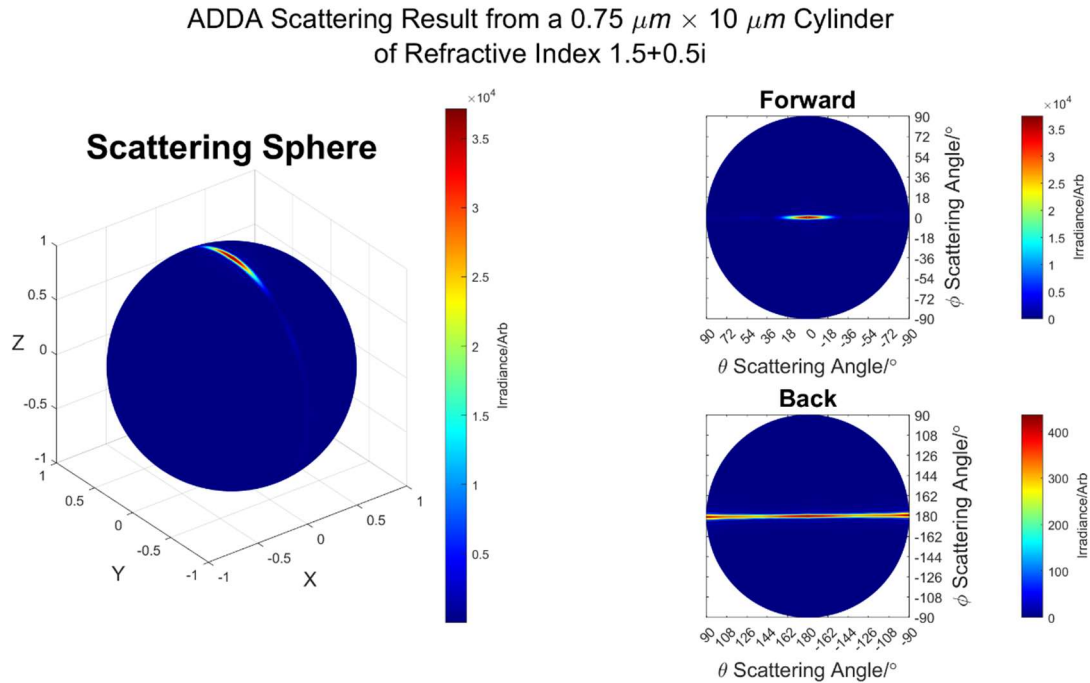


Figure 2.13: ADDA light scattering results of a $0.75 \mu\text{m}$ diameter and $10 \mu\text{m}$ long cylinder of refractive index $1.5+0.5i$, the same as that of Figure 2.12 for the forward and back scattering images (right). Left shows the “scattering sphere”, a more representative representation of the results.

The circular plots were then saved as images in preparation for their comparison with other models. To check that there were no obvious distortion of scattering data between the ADDA output data, shown in Figure 2.11, and processing that data into scattering images, shown in Figure 2.12, a comparison was made and is shown in Figure 2.14. For cylinders of two different refractive indices, $1.5+0.5i$ and $1.5+5e-6i$, parts of the scattering output were compared before and after processing from the ADDA output data into a scattering image. By taking a vertical section (constant θ) through the scattering output of Figure 2.11 for angles of 90° and 270° , the scattering is shown as the orange line in Figure 2.14. The blue line of Figure 2.14 represents the data taken from the central horizontal component (i.e., at a constant θ angle) of the image produced from the ADDA output data.

ADDA Scattering Results of a $0.75\mu\text{ m}$ Diameter and $10\mu\text{ m}$ Long Cylinder Constant θ Angle Comparison

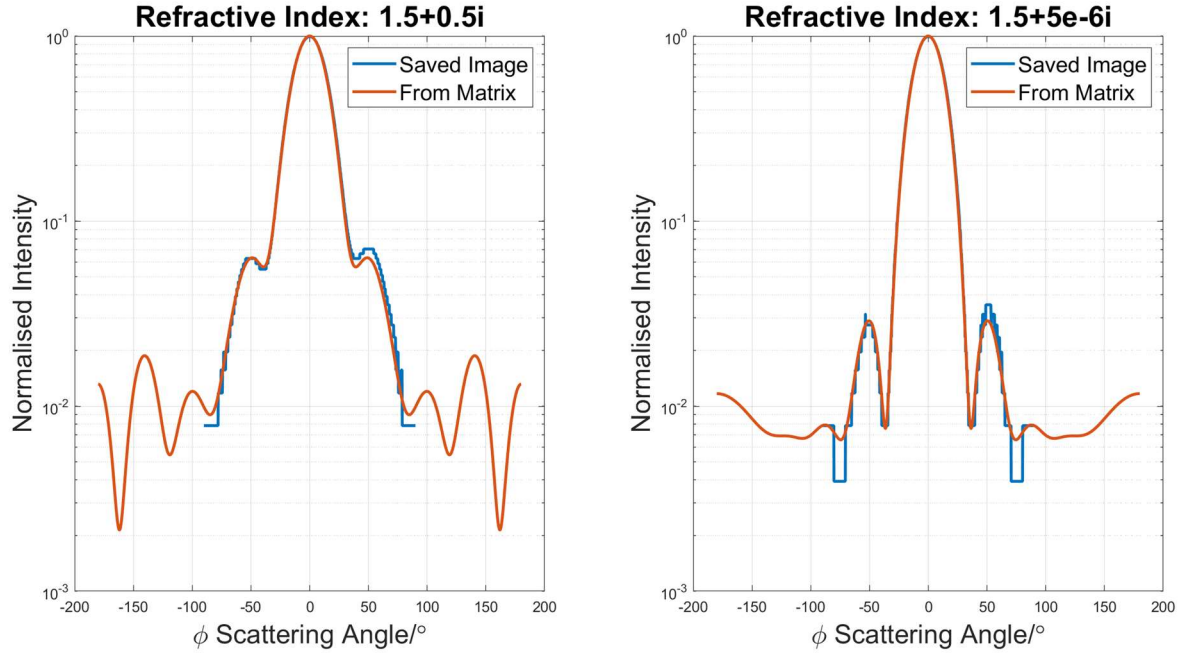


Figure 2.14: Comparison of the ADDA results before and after transforming resultant scattering matrix from square to circular for refractive indices $1.5+0.5i$ (left) and $1.5+5e-6i$ (right). The example used was that of a $0.75\mu\text{ m}$ diameter by $10\mu\text{ m}$ long cylinder and a constant angular value of $\theta = 0^\circ$ was used.

The image data of Figure 2.14 (blue) stops at 90° as only the forward scattering image data was used. There is a reduction in quality, shown by the low resolution of the data, and a slight asymmetry, possibly a result of the image processing method (see Appendix 7.4.1). Fortunately, the asymmetry is negligible, and the resolution can be easily increased.

2.5.3 Limitations

Some limitations of the DDA method are discussed by Yurkin & Hoekstra (2007), wherein a summary comparison to other methods showed to be less accurate than most other models and required much more computer memory, however, the accuracy was suggested to be a factor of the available computational memory. Chaumet (2022) discusses the limitations when considering the material properties of the scattering object, the iteration struggles to converge for materials of a high permittivity and cannot be used for perfectly conducting materials due to the internal field.

Limitations of the ADDA software in particular have also been explored by Yurkin & Hoekstra (2011), agreeing with the DDA limitations stated previously. A combination of the increase in size parameter and the refractive index were attributed to an increasing amount of computational memory requirements. These factors, when of a sufficient magnitude and combination, have also shown to fail in the convergence of the iterative solving process.

Complications of ADDA have been demonstrated in the previous section using examples. The format in which the data are output from the software is confusing and requires additional processing to present the data in a more representative form.

2.6 Ray Tracing with Diffraction on Facets

2.6.1 Overview

A different light scattering model is discussed here that was intended to be used for atmospheric research, which could be considered applicable for this research, known as Ray Tracing with Diffraction on Facets (RTDF). This model was developed relatively recently, from the work of Macke et al. (1996), for the purpose of simulating the light scattered from ice crystals and has been tested against the scattering of ice crystal analogues and data captured by the Small Ice Detector (SID) (Baran et al., 2017; Clarke et al., 2006; Hesse, 2008; Hesse et al., 2009; Hesse & Ulanowski, 2003; H. Li et al., 2024; Stopford, 2010; Ulanowski et al., 2014).

RTDF is based on Geometric Optics (GO) and uses a Monte Carlo-based ray-tracing method that approximates the far-field diffraction pattern of the rays for each facet of the object. This allows the accommodation of large size parameters and high aspect ratios without the need for excessive computational processing when compared with other models. The speckled examples shown in Figure 2.15 and Figure 2.16 are due to the Monte Carlo-based calculations; for each calculation a ray will propagate along the z-axis at a randomised x-y coordinate. The rays' interaction with the object is calculated to find its final trajectory and irradiance. This is repeated for a number of rays, increasing this number will increase the number of calculations and ultimately remedy this speckled effect. Unfortunately, this also increases the time taken to calculate the scattering pattern.

2.6.2 Application

Using the same example objects used throughout, a $0.75\ \mu\text{m}$ diameter by $10\ \mu\text{m}$ long cylinder of refractive indices $1.5+0.5i$ and $1.5+5e-6i$, the model can be tested for its applicability within this research. The output files created from this model are slightly different to that of ADDA, only the S_{11} component of the Mueller matrix is given for the angles of θ and φ , however, the processing is essentially the same. The forward 90° scattering for both the $1.5+0.5i$ (left) and $1.5+5e-6i$ (right) cylinders are shown in Figure 2.15.

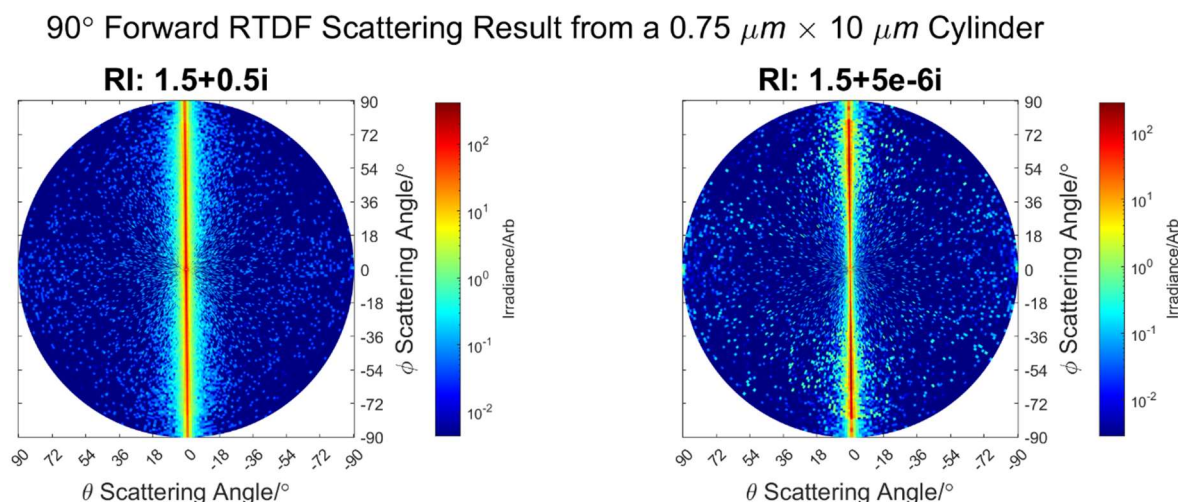


Figure 2.15: RTDF 90° forward light scattering results of a $0.75\ \mu\text{m}$ diameter by $10\ \mu\text{m}$ long cylinder of refractive indices $1.5+0.5i$ (right) and $1.5+5e-6i$ (left).

It is clear that the results are vastly different from those of the examples shown in Figure 2.4, Figure 2.6, Figure 2.8, and Figure 2.12. Most prominent is the speckled effect, however, this may

be ameliorated with an increase in the number of calculations per scattering model. Secondly is the lack of any interference patterns along the bright band.

2.6.3 Limitations

This model can account for more representative crystalline shapes and would make a good emulation of materials like asbestos. Unfortunately, there are limitations on smaller sizes that cannot be explained with GO. The size of the facets of the cylinder used in the example had a width much smaller than the wavelength, when testing on a cylinder of a non-normal incidence – an Euler angle of (0, 20, 0) – the resultant scattering only started to resemble the expected pattern for very small wavelengths, shown in Figure 2.16.

90° Forward RTDF Scattering Result from a $0.75 \mu\text{m} \times 10 \mu\text{m}$ Cylinder of Refractive Index $1.5+5e-6i$ at an Euler Angle of (0, 20, 0)

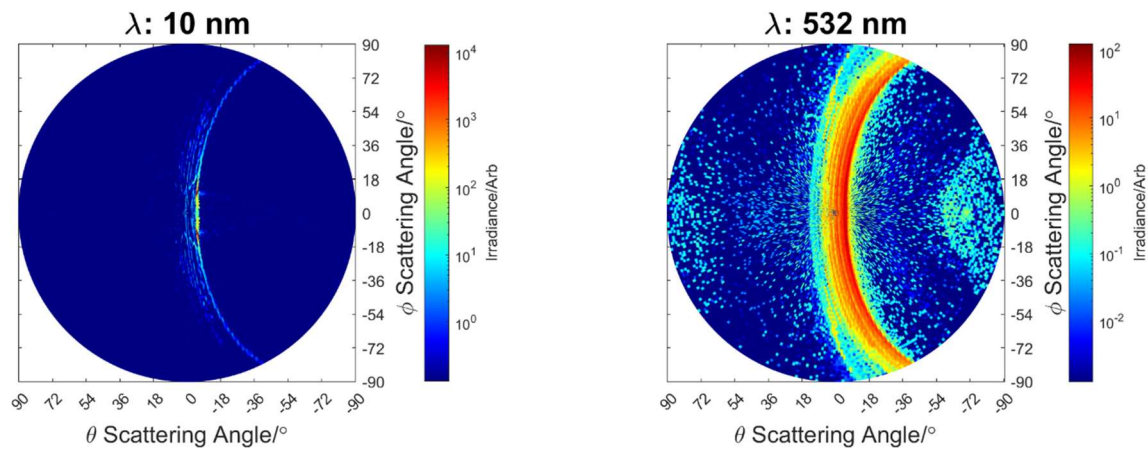


Figure 2.16: RTDF scattering results from a $0.75 \mu\text{m}$ diameter by $10 \mu\text{m}$ long cylinder of refractive index $1.5+5e-6i$ at an Euler angle of (0, 20, 0). The right image shows the scattering when using the wavelength throughout, 532nm, and the left shows the result from using a 10 nm wavelength.

The difference in results of Figure 2.16 are due to this model being GO-based as the reduction in the wavelength results in a size parameter that can be applied with GO. The speckled images will be a problem when trying to analyse any small details, although this may be improved with additional calculations, the time required may become extensive if multiple scattering images are required.

Comparing the bright band to all the examples used hitherto, an interference pattern is expected and a central spot of much greater intensity. This may be the result of this RTDF model lacking any diffraction calculations and being mainly used for particles of much larger sizes. A version of this model that accommodates for external object diffraction does exist, however, the access to these models is limited.

2.7 Parent Beam Tracer

2.7.1 Overview

Another hybrid model, similar to that of the RTDF model, the Parent Beam Tracer (PBT) light scattering model combines GO with surface integration to simulate light scattering from particles. This method by Ballington & Hesse (2024) divides the incident wavefront into triangular beams as it interacts with the object's surface and uses GO to calculate the propagation direction of the beams in the near field zone. The surface integration is then used to

calculate the far-field scattering. The method is designed to be applicable to larger particles and include surface roughness and has been compared with ADDA for both smooth and rough hexagonal columns.

2.7.2 Application

The output files of the PBT are in the same form to that of ADDA and so the process of extracting and preparing the data is exactly the same. The same examples will be displayed; two cylinders of $0.75\ \mu\text{m}$ diameter by $10\ \mu\text{m}$ long, of refractive indices $1.5+0.5i$ (left) and $1.5+5e-6i$ (right) in Figure 2.17.

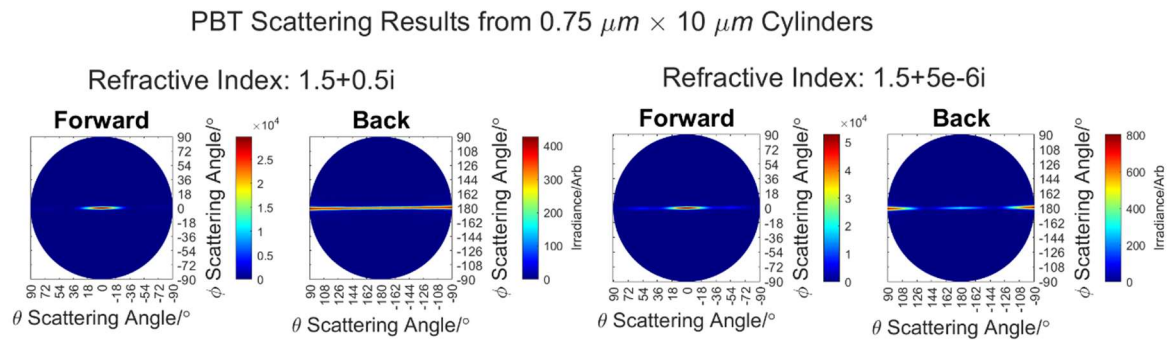


Figure 2.17: PBT scattering results of the forward (first 90° of the ϕ scattering angle) and back (90° - 180° of the ϕ scattering angle) light scattering from $0.75\ \mu\text{m}$ diameter and $10\ \mu\text{m}$ long cylinders of refractive index $1.5+0.5i$ (left) and $1.5+5e-6i$ (right).

The results look reasonably similar to those of ADDA in Section 2.5, with some noticeable differences in the intensity of the back scattering sections. The ADDA data, shown in Figure 2.12, has a distinct difference in the back scattering for the $1.5+5e-6i$ refractive index cylinder when compared with that of Figure 2.17. Interference minima can be seen for the ADDA data at around $\pm 130^\circ$ and $\pm 162^\circ$, whereas the PBT data shows minima at around $\pm 144^\circ$. Again, similar to the RTDF model, this may be a result of an unsuitable size parameter being used and affecting the refractive and reflective scattering. The forward scattering, however, shows no noticeable difference to that of the ADDA results. Additionally, the PBT model took around three to four times less processing time than ADDA.

2.7.3 Limitations

The PBT model is restricted to an incident plane wave, unlike ADDA's ability to have an incident Gaussian beam, this may not be a major issue when simulating small particles scattering light from a large enough beam width, nonetheless it is still a limitation. Although this model is much faster than ADDA, unfortunately, it has been designed to incorporate objects of a much larger size than what is required within this project. A faceted cylinder of small diameter would create facets much smaller in width than the wavelength, resulting in similar issues to RTDF. No noticeable differences were found between the forward scattering of the PBT model and that of the ADDA model, for the examples shown in Figure 2.12 and Figure 2.17, however, as the PBT model was designed for much larger size parameters less confidence is placed in the model producing representative data for this project.

2.8 Comparing Methods

2.8.1 Selecting Candidate Scattering Models

A number of methods have been assessed for their suitability for this project. After weighing the strengths and limitations of the models presented, three have been selected for further evaluation

The simplicity of diffraction theory is its main appeal. When considering potential future instrumentation that could facilitate real-time measurements, a method with minimum computational overheads would be preferred. Results from less absorbing materials however, are discouraging (although not surprising). Nevertheless, the simplicity of this method makes it worth investigating further.

Since an analytical (exact) solution to scattering from an infinitely long cylinder can be found using Mie theory, this method should provide an accurate pattern for diameter measurement investigations. It is thus a useful tool for the current work. Additionally, the computational overhead is much less than alternative numerical methods like ADDA. The key drawback is how to deal with finite fibre lengths but will be ameliorated with the use of the finite length diffraction approximation GLMT, discussed in Section 2.3.2.3.

Lastly, the Discrete Dipole Approximation will be investigated further, particularly the Amsterdam Discrete Dipole Approximation (ADDA) developed by Yurkin & Hoekstra (2011). The reasoning behind the selection of this method, and the ADDA program in particular, are due to various factors, some of which have already been discussed in Section 2.5.1. Another appealing attribute of this software is the level of customisation available. Pre-defined shape files, including cylinders, can be used and modified with input commands, custom shapes can also be generated. Modifications can also be made to the incident beam, orientation of the object, the method in which different equations are calculated, and the level of precision required in the solutions for the iterative solver. The ability of this program to handle fairly large size parameters and objects of a high aspect ratio is also a primary reason for its selection.

2.8.2 Comparing the Three Candidate Methods

Figure 2.18 shows the scattering results, between the angles of -90° and 90° of the forward scattering of each selected light scattering model, ADDA (left), GLMT (middle), and DT (right). The different refractive indices are given as subtitles and the results of the DT scattering are shown twice since diffraction is not a function of refractive index.

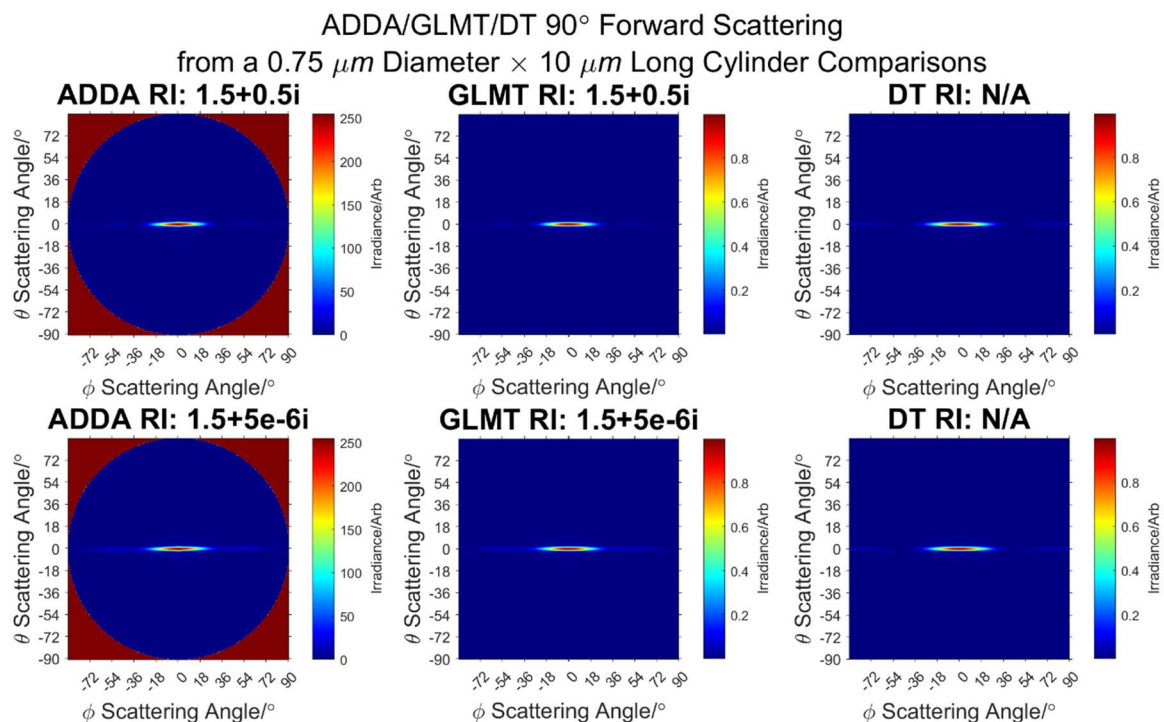


Figure 2.18: 90° Forward scattering results from a 0.75 μm diameter by 10 μm long cylinder from ADDA (left), GLMT (middle), and DT (right). The top rows correspond to a refractive index of $1.5+0.5i$ and the bottom $1.5+5e-6i$ unless otherwise stated.

The red outer part of the ADDA results are from the image saving process described previously; the outside of the circular image is white¹⁴ and so when displayed using this colour map appears red. The scattering patterns of all three models appear to match reasonably well, there is however a noticeable difference between the different refractive indices.

For a more detailed comparison, arrays from the centre of each image were taken. The vertical component is the normalised intensity taken for different values of φ at a fixed angle $\theta = 0$. When comparing the vertical components of GLMT and DT an exact match will be found as the finite length diffraction approximation was used to generate the GLMT scattering image – see Section 2.3.2.3. Figure 2.19 shows this comparison with the vertical components on the left and the horizontal on the right, the more transparent refractive index of $1.5+5e-6i$ is shown in the top rows and the more opaque refractive index of $1.5+0.5i$ is shown in the bottom rows. The scattering angle of the vertical component has been limited between -15° and 15° due to the high number of fringes, to make the plot more decipherable.

¹⁴ In later chapters the default background colour of the images are changed to black to match the images captured by PPD2.

ADDA/GLMT/DT Scattering from a $0.75 \mu\text{m}$ Diameter $\times$ $10 \mu\text{m}$ Long Cylinder Comparisons of Vertical and Horizontal Components

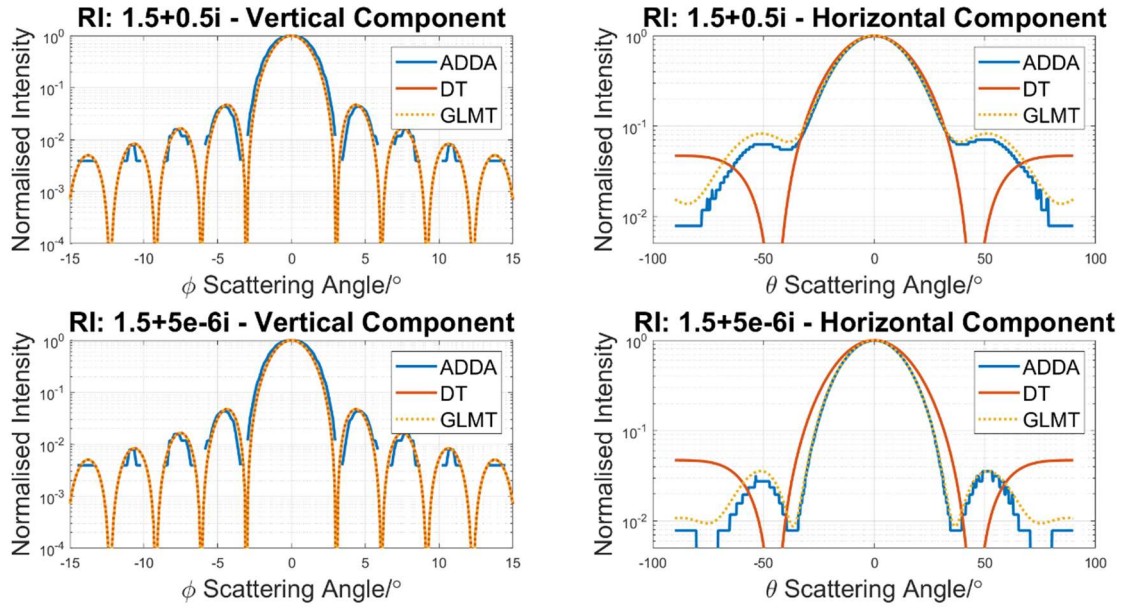


Figure 2.19: Horizontal (right) and vertical (left) components of the forward scattering results from a $0.75 \mu\text{m}$ diameter by $10 \mu\text{m}$ long cylinder from ADDA (blue), GLMT (yellow dashed), and DT (orange). The top rows correspond to a refractive index of $1.5+0.5i$ and the bottom $1.5+5e-6i$.

What can be seen from these results is that the GLMT and ADDA results match well for both the horizontal and vertical components. A larger difference is noticed for the DT results for the horizontal components, even more so for the cylinder of $1.5+5e-6i$ refractive index. The DT results for the vertical components, even though they are the same as GLMT, match well with the ADDA results.

2.9 ADDA Optimisation

Due to the relatively large amount of computer processing time required, compared with that for the other selected models, the settings of ADDA have been explored to reduce the processing time without any diminishing effects of the resultant scattering. Different scattering patterns of the same object were generated and a comparison of their processing time, number of iterations required for ADDA to converge on a solution, and the mean difference of the Mueller matrix S_{11} component were all compared against the default settings.

To start, there are different methods in which the interaction between each dipole is formulated, the manual suggests that some methods may be an improvement from the default, however, they have been studied in less detail and do not include reflection. They were compared nonetheless and showed no noticeable difference in processing time or number of iterations. What was found was a difference in the scattering matrix when compared with the default method and so the interaction term was left as default.

Secondly, there are different methods available in which ADDA iteratively solves the system of linear equations. A series of simulations were carried out using the same cylinder and each available iterative solver. After comparing the factors stated, the iterative solvers were reduced to a selection of two to be used for the last set of tests.

Finally, the iterative solver stopping criterion ε is the relative residual norm, or the accuracy of the solution to the set of linear equations. The value of ε as an input is an integer of the form $\varepsilon = 10^{-(input)}$, and so was reduced from its default value of 5 down to 2 in integer steps for both remaining iterative solvers. Each simulation used a cylinder of 4 μm diameter and 20 μm long, with a refractive index of 1.45+0.0035i and a normal incident angle, i.e., an Euler angle of (0, 90, 0). The scattering results are shown in Figure 2.20 .

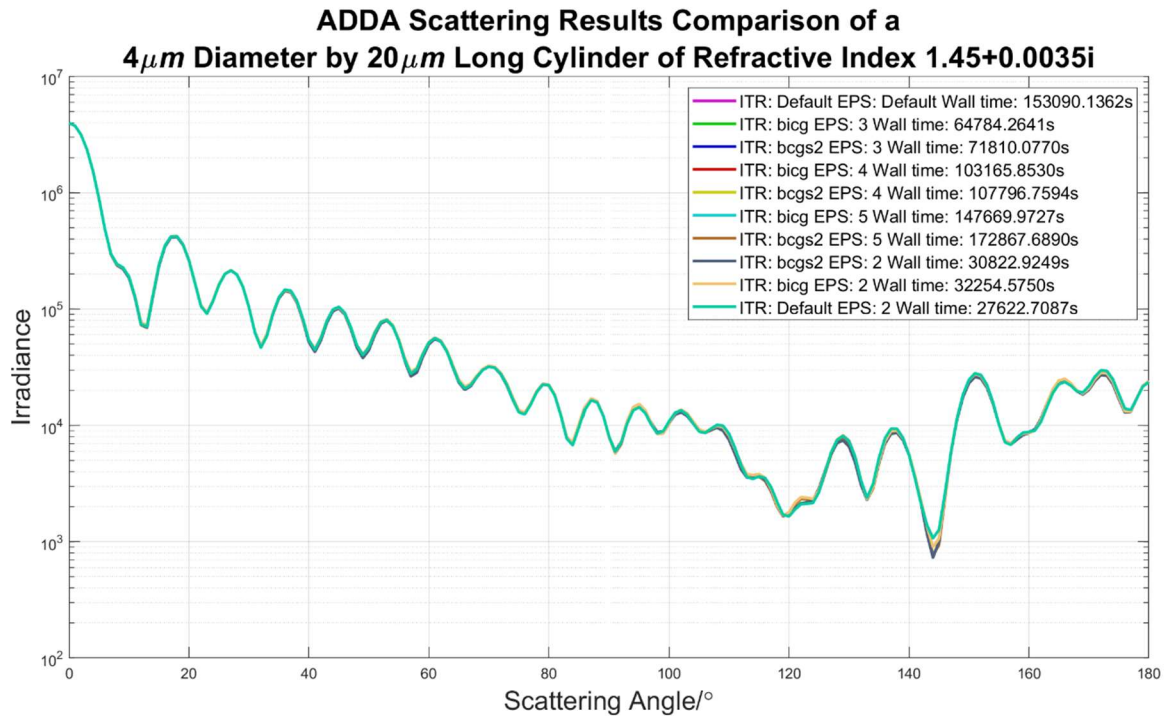


Figure 2.20 : ADDA scattering results of a 4 μm diameter by 20 μm long cylinder of refractive index 1.45+0.0035i using different iterative solvers (ITR) and stopping criterion values (EPS) for comparison.

The key for the plot in Figure 2.20 indicates the different iterative solvers (ITR) used and the value of ε (EPS) entered. Immediately, it can be seen that there is very little difference between the different scattering patterns that only becomes noticeable after around 100°.

The minima found for the data in Figure 2.20 can be used as a means of comparison. The difference in angular location (labelled as “Angular Difference” in Figure 2.21) of each minima of the same order (i.e., the order of the 1st minima are all around 10° of Figure 2.20, the 2nd around 23°, etc.) to that of the default settings of ADDA. These differences are shown in Figure 2.21 and include the processing time taken, indicated in the key as “wall time”.

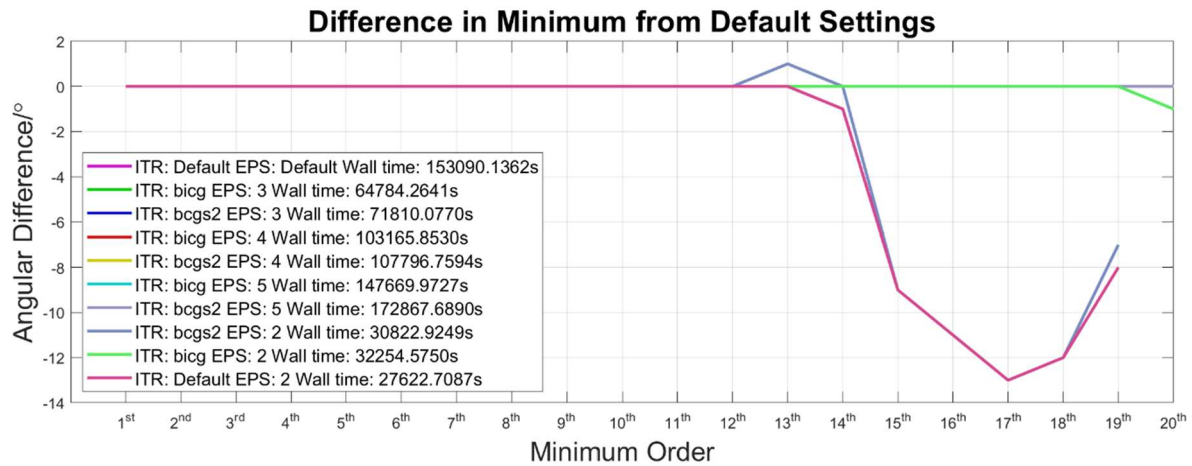


Figure 2.21: The difference in minimum compared with the default settings from the ADDA scattering results of a $4\text{ }\mu\text{m}$ diameter by $20\text{ }\mu\text{m}$ long cylinder of refractive index $1.45+0.0035i$ using different iterative solvers (ITR) and stopping criterion values (EPS) for comparison.

No difference in minimum from the default settings are found until the 13th order minima, corresponding to a scattering angle beyond 100° . Considering these results, the combination of stopping criterion and iterative solver was decided for the duration of this project to be an ϵ value of three and the iterative solver to be the bi-conjugate gradient, enhanced, and stabilised method (bcgs2) described by Fokkema (1996). Although there were much faster results, e.g. using the default iterative solver and an ϵ value of 2, the chosen settings showed no deviations from those of the default and were considered more reliable.

2.10 Conclusion

A multitude of light scattering models are available, as detailed by Kahnert (2003), but an exhaustive investigation into each would be incredibly laborious. However, it should be noted that many of the models are very similar to one another, the choice is not as broad as it might appear. The models presented here have been chosen for their potential to simulate light scattered from fibrous objects. Additionally, these models are sufficiently different to warrant investigation and comparison.

The three methods selected all show a reasonable agreement with each other, aside from DT for more transparent materials.

The intention of this chapter was to investigate different methods of simulating light scattered from high aspect ratio objects and their applicability to be used within this project. Evidently, there are a plethora of ways to emulate light scattering, but only a handful possess qualities that enable their use within this project. The following chapter will compare these models to the light scattering measured from real fibres to test their validity of their use as a measurement tool.

3 Static Fibre Experiment

“The world was to me a secret which I desired to divine.”

-Marry Wollstonecraft Shelly, Frankenstein; Or The Modern Prometheus, 1818

3.1 Introduction

3.1.1 Motivation

The following experiment was conducted to explore the validity of the light scattering simulations investigated in Chapter 2. The scattered light from fibres of different diameters and refractive indices have been measured and compared to the light scattering produced by the various selected models. By comparing the results of the experiment and light scattering simulations, an informed decision can be made regarding the use of these simulations and how representative they are of real data. Different features of the scattering may also be used as an indication of a possible measurement technique.

The samples used in this experiment have a diameter greater than that of the WHO size parameters for respirable fibres, due to availability and handling limitations. Although this is not ideal, a comparison of the results will provide adequate evidence of how representative each model is to the corresponding measured data.

3.1.2 Similar Experiments

3.1.2.1 Review

Similar experiments have been conducted using various fibre diameters, materials, and methods of measurement and models. Farone & Kerker (1966) created sub-micron diameter fibres of fused silica and Pyrex by rapidly pulling glass or Pyrex rods over an oxygen-propane flame. The resulting liquid would quickly solidify in a fibrous form and deposit on some black card to be used for the light scattering experiment. The fibres were mounted onto a C-shape device and placed into a modified light scattering photometer where the scattering patterns from two wavelengths (436 nm and 534 nm) were measured between 15° and 130° of the forward scattering direction. The results were compared to those of Mie theory for infinitely long cylinders and determined the diameter of the glass fibre within 1% accuracy and the Pyrex fibre between 13% and 26%. The inaccuracy of the Pyrex results were attributed to a possible curvature of the fibre and a slight misalignment within the photometer. Other problems were documented, mostly with fibre preparation, where the pulled fibres were hard to see and manipulate onto their mounts. Additionally, the fibres would often break at various stages throughout the experiments and even with just a slight change in air current. Larger diameter fibres were mentioned, however, they would require a much larger number of calculations for an accurate comparison and were not included in the results.

Watkins (1974) conducted a similar experiment on larger clad fibres that contain a different core refractive index. A fibre was mounted in the centre of a rotational stage on which was attached a silicon photodetector. This was automatically rotated via a motor and measured the scattering pattern from a fixed He-Ne¹⁵ laser of wavelength 633 nm. An aperture ensured a resolution of 0.2°. As the fibre diameters were relatively large, ~20 µm for the inner core diameter and 40 µm ~ 166 µm for the outer shell diameter, both an infinite cylinder model and ray tracing were used

¹⁵ Helium-Neon.

for matching scattering patterns. By observing the scattering between the angles of 30° and 80°, a diameter measurement within ~2% by counting the number of fringes (maxima) was achieved. Discrepancies between the theoretical and experimental results of the scattering patterns were attributed to a wrongly assumed refractive index, the core refractive index was unknown and shown to be a crucial part in the accuracy of measurement. Other differences in the results were speculated to be potential misalignment of the fibre within the beam or the fibre not having a completely circular cross section. Additionally, scattering angles greater than 85° were reported to show a much worse match to theoretical data than that of the forward direction.

Van Der Meulen & Strackee (1979) and Bell & Bickel (1981) also conducted similar experiments using fused silica fibres within the 1 µm – 10 µm range. The refractive index of the fibres were not explicitly stated in the literature, however, one can assume they were known due to the fact that the material the fibres were made from was known. Fibres were constructed in a similar manner to Watkins (1974) and Farone & Kerker (1966) and both used infinite cylinder scattering for matching. Van Der Meulen & Strackee (1979) used both minima counting between 0° and 90° and forward light scattering integration between the angles of 16° and 30°, the latter method was described similarly to how an OPC would work and required calibration. The measurement of the fibre diameters was found to be better than 1% for the minima counting method and ~5% for the forward scattering method. Bell & Bickel (1981) included the use of alternating polarisation, whilst conducting measurements, to measure each polarisation state of a Mueller matrix – later shown to be unnecessary. Again, a count of the peaks of the scattering between 5° – 160° were reported to give a size parameter measurement within 10%, this was found to work for each state of polarisation measured. Similar to Watkins (1974), beyond a scattering angle of 70°, the match between measurements and theory were shown to diminish.

3.1.2.2 Discussion

The construction of glass fibres within the 1 µm – 10 µm range has been reported to be an arduous task. Further, the manipulation and measurement of those fibres, without substantial breakage, was shown to be a very time-consuming process. The larger diameter fibres, measured by Watkins (1974), had no reports of any problems during these processes. However, the diameters used were up to two orders of magnitude larger than the other experiments. The methods in which the scattering data were measured all reported a similar process, with slight variations in the equipment and measurement angles, but could be easily replicated with basic lab equipment. The success of using the minima or maxima count between angles is a promising idea, however, each sample examined was glass-like and shared a similar low imaginary refractive index. This method may provide a less accurate measurement when a more absorbing material is used, as none of the reviewed literature used materials of a high imaginary refractive index. Additionally, smaller diameter fibres of ~1 µm and less would have very few minimum or maximum points within the range of accessible scattering angles, some of these points may be found beyond angles where the measured and modelled data showed less of a match in the literature.

3.1.3 Considerations to the Following Experiment

Consideration of such previous work has informed the design of the current experiment. Small diameter fibres will be used, however, to prevent excessive time lost to failures in the manufacture such fibres or excessive breakage, fibres of less brittle material and of a diameter ~10 µm will be used. This will require more computational time for the more complex light scattering models (ADDA), due to the size parameter, however, the University of Hertfordshire's

High-Performance Computing (UHHPC) facility is able to conduct many of these calculations simultaneously in a reasonable amount of time.

A similar experimental setup to that adopted by Watkins (1974) will be used but with a manual measurement system – the construction of a synchronous measurement device may take as long as measuring the fibre scattering manually. The resolution of the measurements were higher in the forward scattering direction and lower at an angle greater than 50°, because of the back scatter problems found in the literature. Readings of the back scattering are still needed but expected to not match well with theoretical data, as discussed in the previous section, a lower resolution will save time. Finally, for greater accuracy of the fibre diameter measurements, scanning electron microscopy (SEM) will be used in the analysis of the diameters of the fibres, post-light scattering measurement. Using SEM for the measurement of the fibre diameters will ensure a greater accuracy of the measurement in comparison to optical methods. Additionally, as discussed in Chapter 1, the WHO-recommended techniques for fibre counting is phase contrast optical microscopy (PCOM), but any additional evaluation of the fibres is done via electron microscopy.

3.2 Equipment

3.2.1 Instrumentation

3.2.1.1 *Available Equipment*

The equipment used for this experiment consisted of a photo-multiplier tube (PMT, Hamamatsu Photosensor module H9306-04) and its power supply (Hamamatsu C7169), a 658 nm alignment laser diode (The Optoelectronics Company Ltd.) focused with an $f = 35$ mm plano-convex cylindrical lens, a 532 nm CW laser (Global Laser, Firefly) focused with an $f = 50$ mm plano-convex spherical lens, a power supply (TATA EX354RT), an oscilloscope (Tektronix TDS2024C), a rotational stage, and various translation stages for alignment. The 50 mW laser, tuned down to a power of 1 mW, was measured (using a Newport LBP2-VIS2 camera) to have a circular beam profile of ~ 18 μm diameter at the focal plane. A laser power meter was used to measure the laser power (Thorlabs PM100D).

3.2.1.2 *In-House Manufacturing*

The 3D printed sample mounts are shown in Figure 3.1. The bottom angle bracket was designed to be bolted onto an optical post and to the two flat plates of the fibre holder, the single mounting point allowed for adjustments to be made considering the alignment of the fibre. The two plates would then sandwich a sample, held within the small cut out. The fibre was first mounted to a similarly shaped card slide to ensure a stable mounting to the 3D printed parts. Any exposed parts, such as bolts, card, etc., were then painted with Black 3.0 (CultureHustle) to minimise any unwanted light scattering that could potentially interfere with the PMT readings.

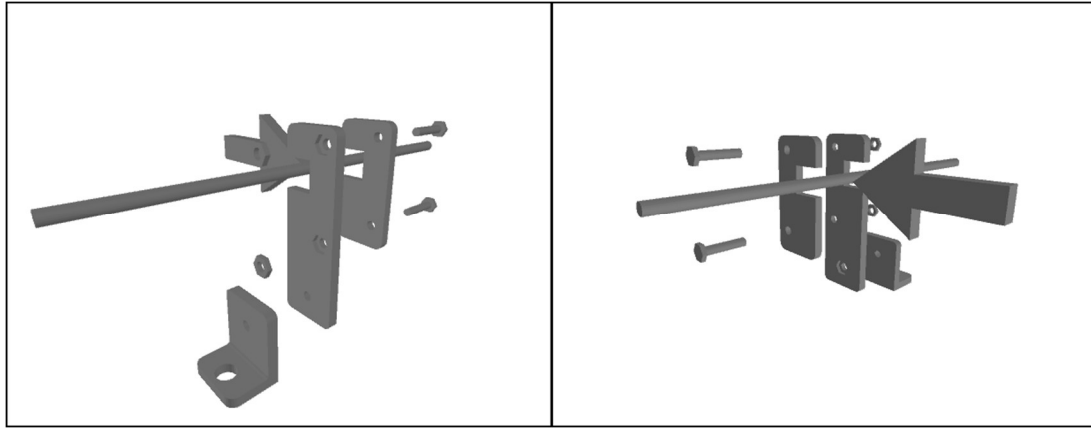


Figure 3.1: 3D renders of the fibre mount STL files, the long cylinder indicates the position of the laser and the arrow indicates the location of where the fibre is located. (Nuts and bolts included for instructive purposes, not actually printed).

An aperture was also made to be mounted in front of the PMT, this was to improve the angular resolution of the experiment. The aperture of the PMT was measured to be 3.7 mm $\times$ 13 mm, this was slightly reduced by an additional aperture, located in front of the shutter, to ensure a resolution of 0.25° at a distance of 800 mm and to minimise possible errors from scattering in the φ direction¹⁶. The aperture was constructed of an aluminium disk, covered in a self-adhesive, light absorbing material, with a 3.5 mm diameter hole punched in the centre and mounted in an optical tube.

The PMT shutter/housing was designed for the PMT to be mounted using M2 bolts through the four holes on the face of the object in Figure 3.2. These mounting holes also served to join the shutter component of the housing together. The hole in the centre of the bottom section was designed to fit an M6 bolt to be mounted to an optical post. The round disk rotates about a hinge at the bottom of the square aperture on the front face to cover the PMT when not in use.

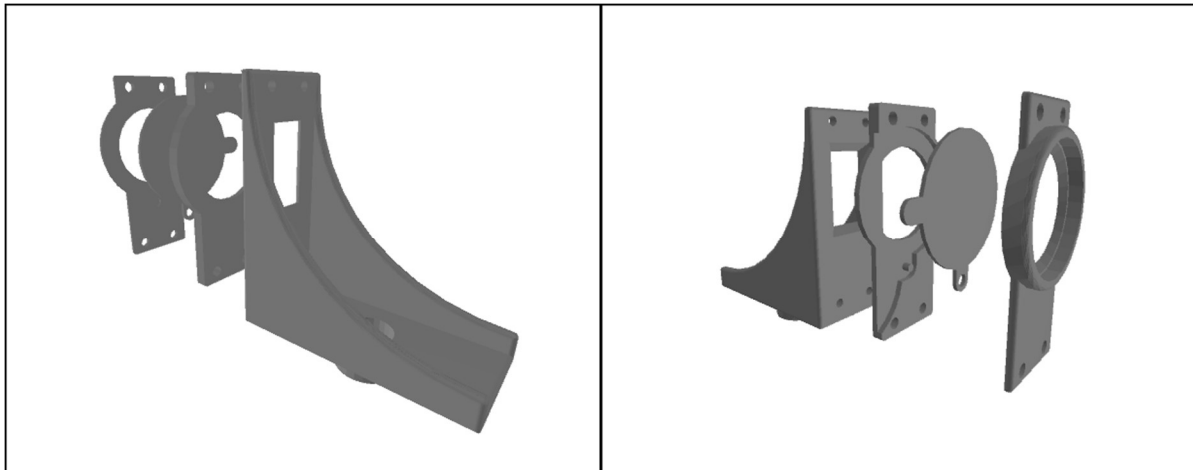


Figure 3.2: 3D renders of the PMT mount and shutter STL files. Both the 3D printed parts and the PMT are bolted together through the four holes, the circular shutter rotates about a hinge to protect the PMT when not in use.

The laser housing had no mounting points and so a mount was designed that could be used in conjunction with the available optical bench components. The laser housing fits in the centre of the tube and the two tabs along the top are used to bolt together and pinch the laser in position,

¹⁶ See Section 1.2.2.

shown in Figure 3.3. The ends of the mount were designed to fit on to a standard 1" cage plate adaptor to help mount it to the optical breadboard.

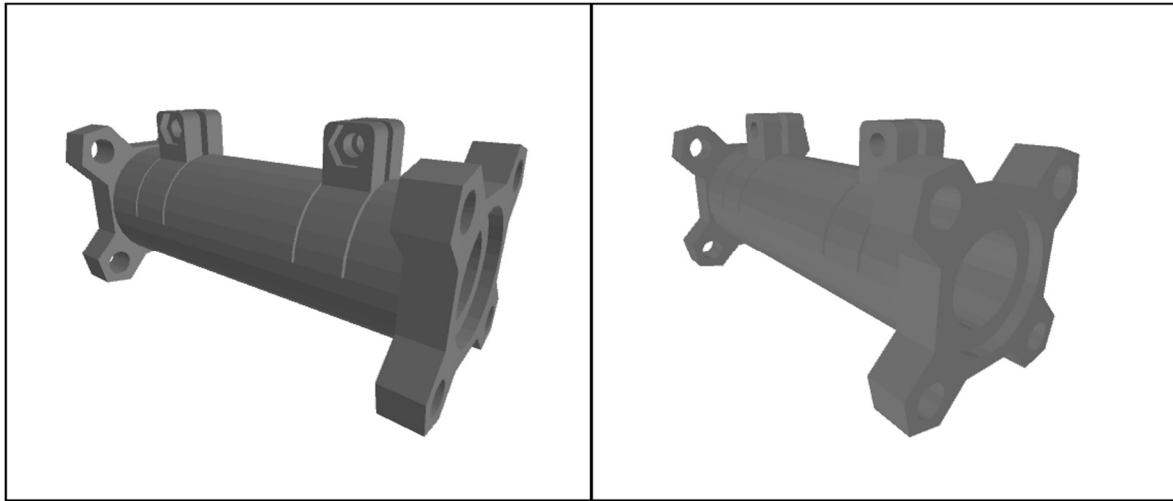


Figure 3.3: 3D renders of the laser mount STL file. Designed to fit to a standard 1" cage plate adaptor, the laser is held in position by two pinch bolts.

To maximise the amount of data available to be measured, and to prevent the laser shining directly into the PMT, a thin beam-stop was also designed and 3D printed, shown in Figure 3.4. The laser passes through the 3 mm wide opening and is reflected by a 45° mirror downwards towards some light absorbing material. The reasoning behind this was an attempt to minimise any stray light scattering that occurred with other previous attempts at constructing a beam-stop.

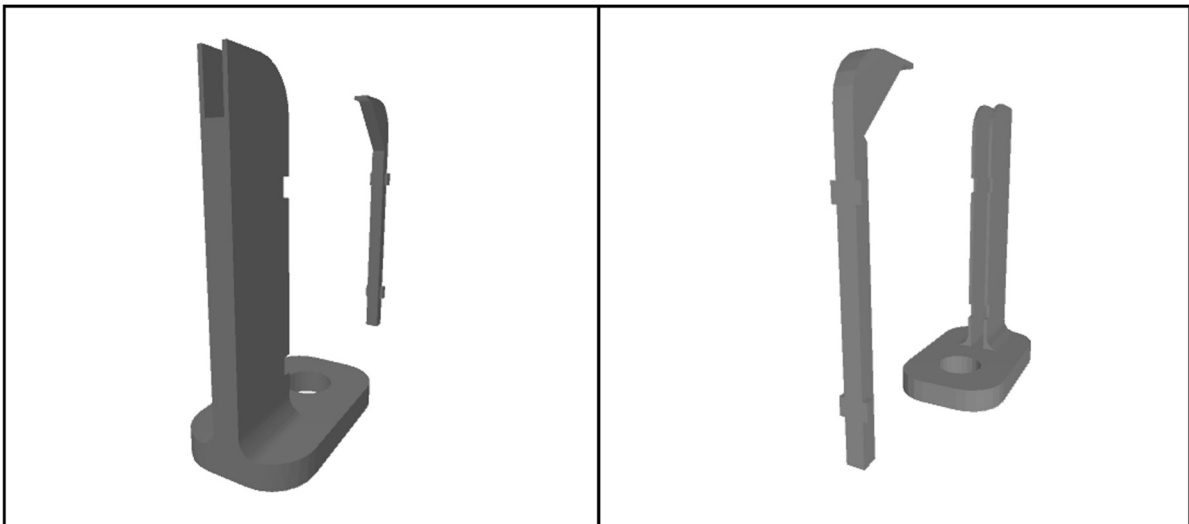


Figure 3.4: 3D renders of the beam-stop STL file. A small mirror is glued to the 45° angle of the smaller cap, where the beam is diverted to minimise stray scattering.

An alignment tool was a simple aluminium billet at 40 mm diameter, shown in Figure 3.5. One end was turned down to a diameter 32 mm to have a sliding fit into the centre of the rotational stage. The top had a small hole drilled into the centre where a pin was located. Further details on how this was used is given in Section 3.3.1.4.

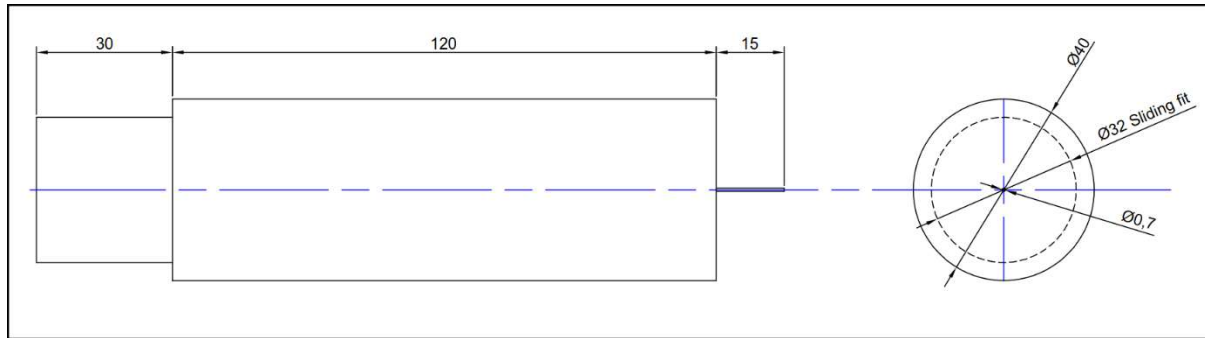


Figure 3.5: Diagram of aluminium alignment tool.

3.2.2 Samples

3.2.2.1 Justification of Samples

Two different materials were selected, carbon fibre and glass fibre, which have differing physical and optical properties. This was done to ensure a reasonably fair distinction between them, one having quite absorbing properties, and the other a relatively low imaginary part of the refractive index. Both are materials that can be found in fibrous form and are fairly common in everyday life. Although both samples had a much larger diameter than the respirable range, the ultimate focus of this project, it is not important for the assessment of the scattering models.

3.2.2.2 Carbon Fibre

The first sample was carbon fibre, shown in the scanning electron microscopy (SEM) image in Figure 3.6 and taken post-scattering data measurement. According to Ermolaev et al. (2020), the refractive index of carbon fibre at a wavelength of 532 nm has a value of $1.5666 + i0.42439$. There was no means available of measuring the fibres refractive index and so this value is taken to be an approximation for this experiment.

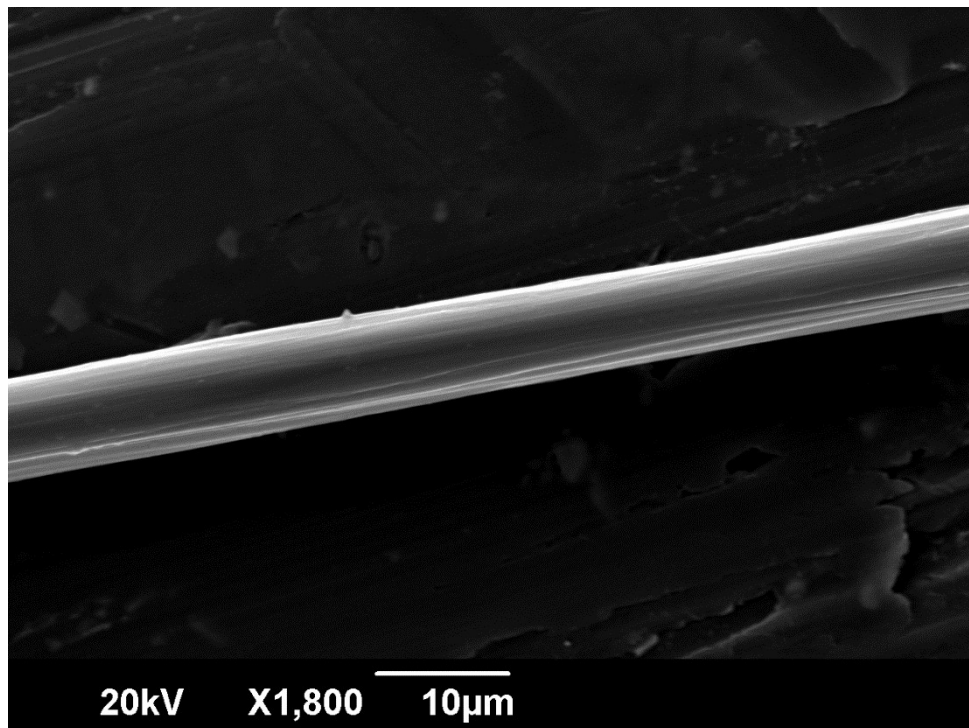


Figure 3.6: SEM image of carbon fibre sample.

The sample was analysed (using ImageJ) along the length in five separate places and was found to measure $7.3 \pm 0.3 \mu\text{m}$. The sampling error of the measurement was obtained from the standard error:

$$Error = \frac{\sigma}{\sqrt{n}}$$

Equation 3.1

Where σ is the standard deviation of the measurements and n is the number of measurements.

3.2.2.3 Glass Fibre

The second fibre sample was a type of reinforcement fibreglass from a woven mat, Figure 3.7 shows the SEM image of the sample – the top fibre was used for this experiment. The fibreglass sample used was a type of “E-glass”, commonly used for the structural reinforcement of printed circuit boards and other electronic components (Kister et al., 2003), hence the E- prefix. The chemical composition of E-glass generally consists of ~55% silica and includes various oxides such as calcia, magnesia, alumina, etc. (Chawla, 2001). No literature was found regarding the refractive index of this material at the desired wavelength and so has been assumed to be the same as silicon dioxide at a wavelength of 532 nm – $1.4668 + 0.0019918i$ (West et al., 2016). This value will most likely not be correct due to the additional oxides and may need to be altered to better match the scattering pattern of the measured data.

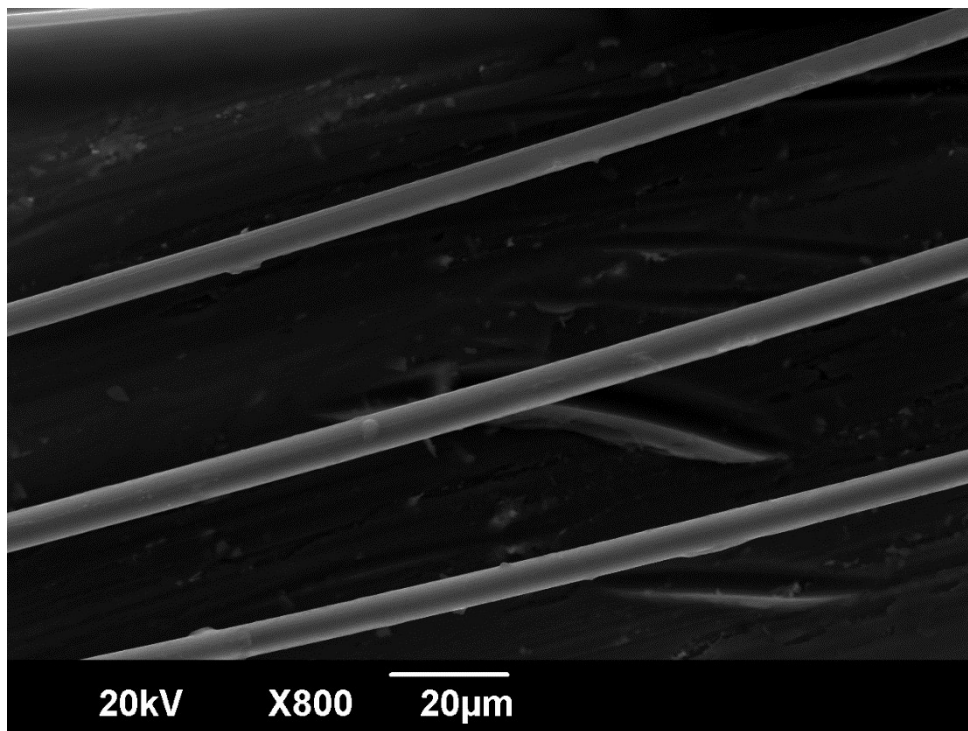


Figure 3.7: SEM image of glass fibre sample. Top fibre used for this experiment.

Again, five measurements along the fibre were made to find a diameter of $5.2 \pm 0.1 \mu\text{m}$.

3.3 Method

3.3.1 Set-Up

3.3.1.1 Equipment Layout

The set-up of the experiment is shown in Figure 3.8, along with photographs of the alignment procedure. A rotational stage was mounted to the optical breadboard and aligned to ensure that the 0° angle was aligned horizontally to the page, in the direction of the PMT. An aluminium plate was then mounted to the rotational stage offset to one side, this is where the 2D translational stage for mounting the green laser and focusing optics was mounted. A 1D translational stage was mounted perpendicular to the green laser for the red alignment laser. The PMT was mounted within its shutter to the breadboard 800 mm from the centre of the rotational stage, an optical tube was mounted in front of the PMT to house the aperture. Finally, after alignment, another 2D translation stage was mounted at the centre of the rotational stage, this was used to align the fibre samples and the beam-stop.

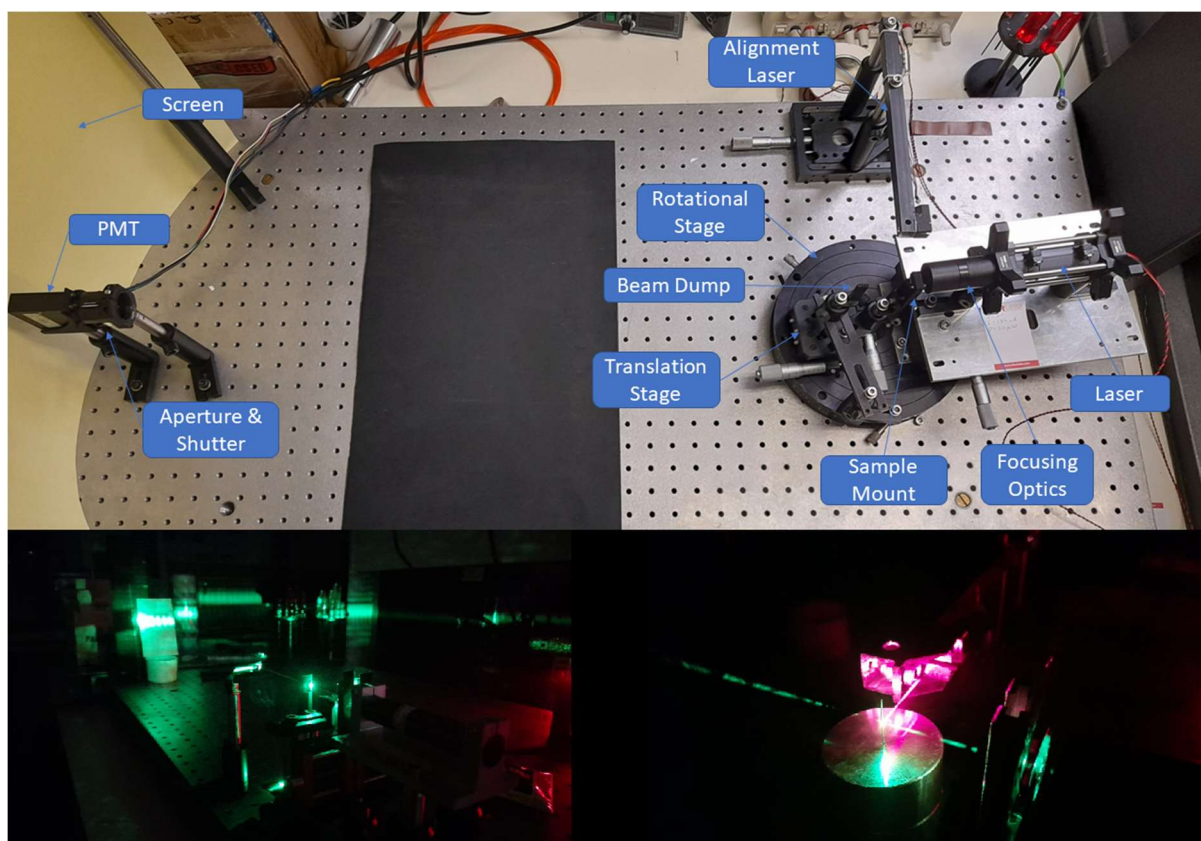


Figure 3.8: Photograph of experimental setup (top), including labels and part of the alignment process (bottom).

A diagram of the experimental set-up is also included, shown in Figure 3.9, for clarity.

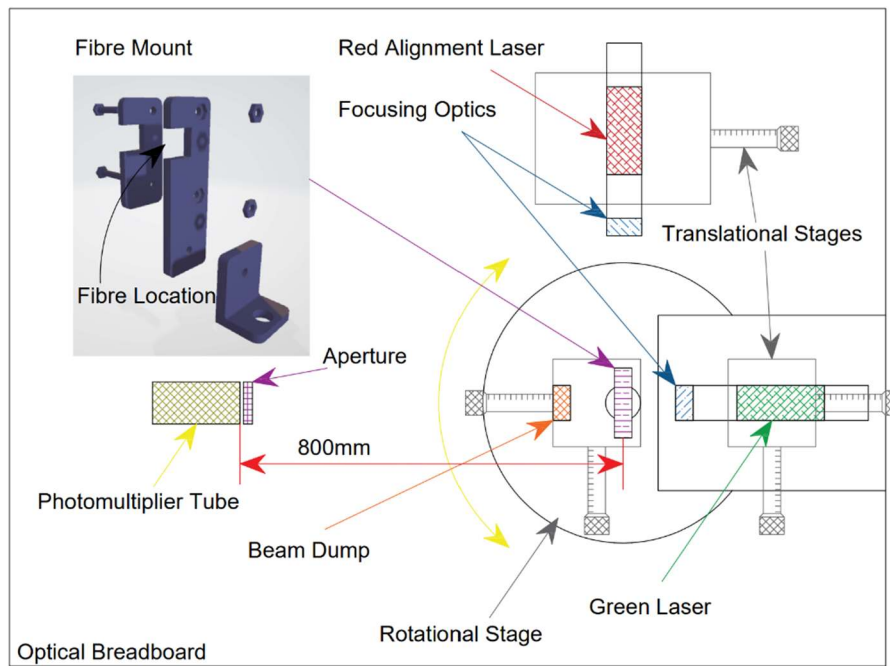


Figure 3.9: Experimental layout diagram.

3.3.1.2 Sample Mounting

After the samples were separated from bundles using tweezers, magnifying lenses, breath-holding, and plenty of patience, they were glued into the crease of a folded cardboard square. This cardboard square had a square hole in the centre and so after the fibre sample was glued in and folded, the cardboard square now resembled a C shape. The sample, now mounted in the cardboard, was then clamped in position by the 3D printed mount, as described previously. The mount was then attached to a 2D translational stage. Figure 3.10 summarises the process of mounting the fibre, first with the cardboard mount (left), the fibre mounted to the cardboard (middle), and finally the fibre mounted to the 3D printed mount (right).

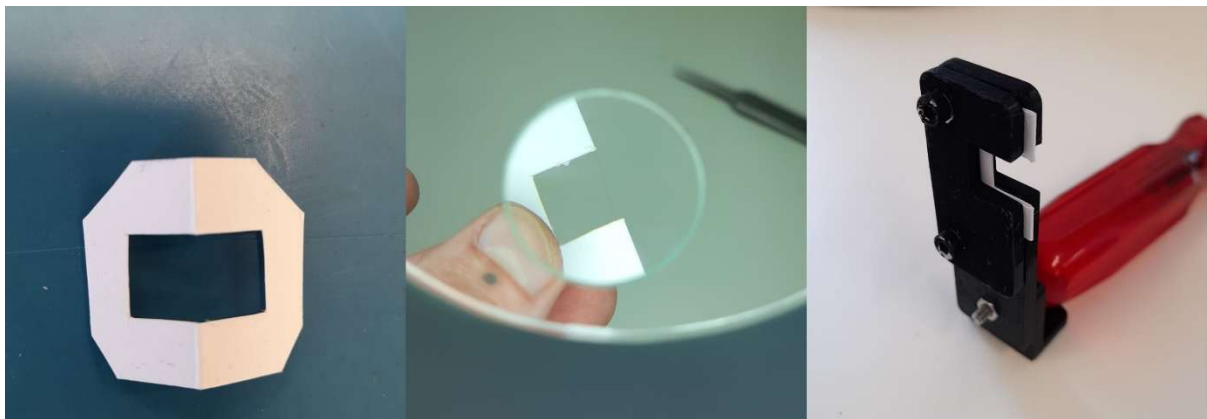


Figure 3.10: Photographs of the prepared cardboard mount (left), the mounted fibre in the cardboard mount (middle), and the fibre mounted in the 3D printed mount (right).

3.3.1.3 Focusing

To ensure the focus of the laser was correctly positioned, it was first located so that the focusing lens was around 50 mm from the central location, where the face of a beam imaging camera was located. The face of the imaging camera was initially marked using the alignment tool. The laser was then powered on at a low setting and the beam profile was monitored on the

camera software. The translation stage with the green laser was then adjusted (left and right of the page for Figure 3.9) to minimise the size of the beam spot and measured to be $\sim 18\text{ }\mu\text{m}$ in diameter.

3.3.1.4 Alignment

To ensure the fibres were mounted in the centre of the rotational stage, the aluminium alignment tool was used. Before mounting the 2D translation stage for the sample, the alignment tool was inserted and both lasers powered on at a low setting, see Figure 3.8 (bottom right). Interference fringes were then observed on the far walls and the translation stages adjusted until the fringes appeared symmetrical. The red laser, used solely for alignment, had no need to be focussed and was adjusted left and right (of the page) to coincide with the alignment pin. The adjustment of the green laser was similar but up and down of the page, as it had already been adjusted to ensure the focus was central to the rotational stage. To test the effectiveness of the alignment, the setup was rotated to see if any changes in the interference fringes on the far wall occurred and then adjusted accordingly to minimise these changes.

After aligning the lasers to the centre of the rotational stage the alignment tool was removed. The 2D translation stage for the sample mount was then mounted in its place. The aligned lasers were then used to correctly position the fibre sample using slight adjustments of the translation stage where the sample mount was attached. The same technique was used to ensure the sample was central by observing the interference patterns on the far wall and rotating it to observe for changes from the red laser. Finally, to check the fibre was correctly aligned vertically, the centre of the scattering from the green laser was marked on some card, see Figure 3.8 (bottom left), then rotated to see if there was any noticeable curvature. If there was, it was corrected for by slight rotations of the fibre mount and the entire sample alignment procedure repeated.

3.3.2 Data Acquisition

3.3.2.1 Measurements

The light scattered from the sample was divided into sections defining scattering angle ranges relative to the propagation direction of the incident laser. The propagation direction was 0° . The sections were divided into $0^\circ - 20^\circ$, $20.5^\circ - 50^\circ$, and $51^\circ - 160^\circ$ and are referred to as the Forward (FS), Side (SS), and Back Scattering (BS) sections respectively. Within each section a different angular measurement resolution was used, namely: 0.25° , 0.5° , and 1° for the FS, SS, and BS sections respectively. This was decided as more information was expected to be found in the FS section, less in the SS section, and almost none in the BS section, as was discussed in the introduction to this chapter.

The gain setting of the PMT was first turned all the way down. The scattering pattern, after letting the laser warm up and stabilise, was rotated to have the brightest part aimed at the PMT aperture. The gain of the PMT, monitored with an oscilloscope, was then increased enough to ensure no damage would be caused.

Starting at 0° rotation, where there would not be any light detected, the rotational stage was locked. The output of the PMT was then saved by the oscilloscope to an external storage device as a series of voltage measurements. The rotation stage was then unlocked, rotated by the amount required for that section, and the process repeated. For the measurement of the BS section, as the irradiance of the scattered light was so low, the gain of the PMT was increased and a stop was made to prevent the stage being rotated back too far to protect the PMT.

3.3.2.2 Calibration

To convert the voltage readings from the experiment into power, the PMT was removed and replaced by the laser power meter. The angle was noted, and a power reading was taken for each gain setting used in the different scattering sections. The data was then normalised from a voltage reading to a value of power accordingly.

3.3.2.3 Limitations

Light scattered in the very forward direction was not obtained due to the beam stop, this was found to be around 3° from the 0° centre point. There was an upper limit at around 160° due to the apparatus blocking some of the BS section when rotated into position. Additionally, the scattering was only measured on one side of the total pattern, also done in the experiments reviewed in the introduction, as more of the apparatus would otherwise have been blocking the resultant scattering image.

The samples themselves were very problematic, especially the glass sample. First, the separation of the individual fibre from the fibre bundle was challenging. The separated fibre also had to be of adequate length to fit within the sample mount. Mounting that separated fibre onto the cardboard mount also proved difficult. Additionally, all this was performed under illuminated magnification and required a great deal of dexterity and patience, not to mention luck. After several successful mounts of a sample, most were damaged by air currents whilst being transported from the mounting station to the experimental setup.

Another time-consuming problem was the measurements themselves. Around 250 measurements were needed for each sample and each measurement made by the oscilloscope took around 20 s to record the voltage to a file.

3.4 Results

3.4.1 Carbon Fibre

Results of the calibrated carbon fibre light scattering are shown in Figure 3.11, a logarithmic scale for the power has been used due to the high dynamic range of irradiance and to emphasise some of the SS and BS sections as their irradiation levels were much lower than that of the FS section, as expected.

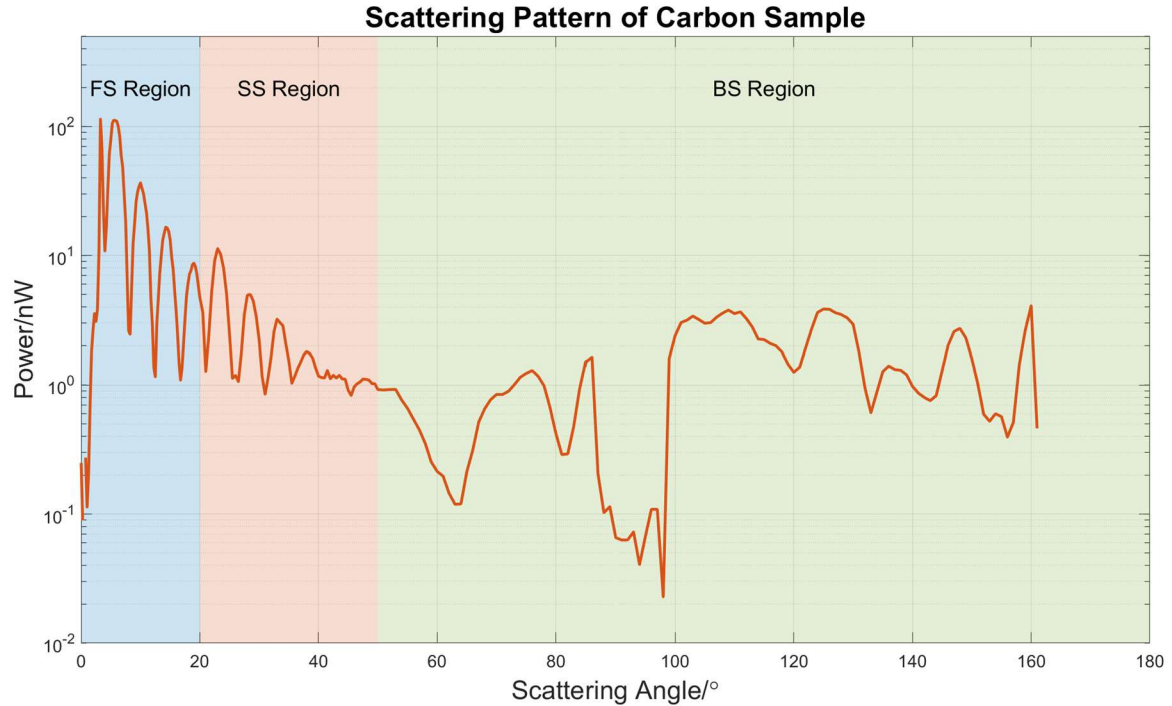


Figure 3.11: Light scattering results from carbon fibre sample shown on a logarithmic scale for the power, plotted against scattering angle. The forward scattering (FS), side scattering (SS), and back scattering (BS) regions are shaded blue, red, and green respectively.

As stated previously, no data are measured beyond 160° due to the setup and from 0° ~ 3° contains mostly noise from stray light scattered by the beam-stop. Beyond the 40° point the scattering measured becomes quite erratic, this may just be noise from the high gain required to detect a signal using the PMT. As carbon has a high imaginary refractive index the scattering was expected to be dominated by diffraction effects, not much scattering was expected to be found in the SS and BS sections. The lack of reliable readings for the larger scattering angles was anticipated, as discussed earlier, however, this angular limit was surprisingly more acute than expected from reviewing the literature.

3.4.2 Glass Fibre

The results for the glass fibre sample are shown in Figure 3.12 and on a logarithmic scale like the carbon fibre results. Compared with the results for the carbon sample, the interference pattern is much clearer beyond the previously noted 40° limit, continuing to around 80° before the results become unpredictable and noisy. This is unsurprising as the experiments reviewed earlier showed a similar outcome. When comparing this to the results for the carbon sample, having a much higher imaginary refractive index, speculation into the cause of this may lie in the greater amount of refraction and reflection involved from the more transparent nature of the material.

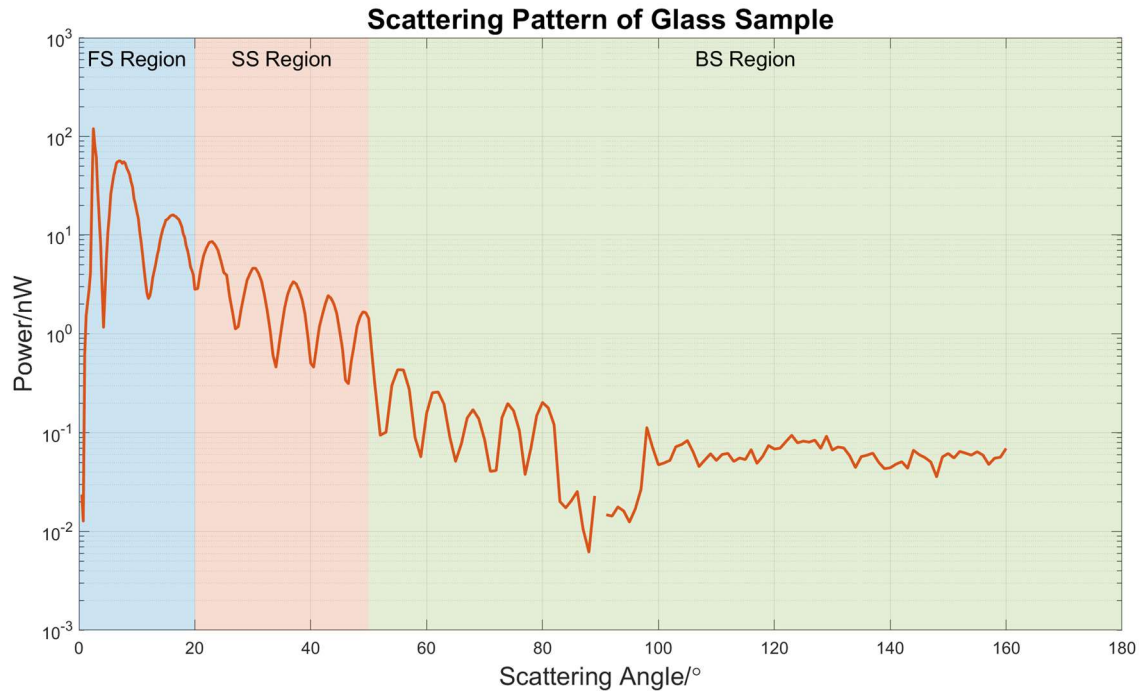


Figure 3.12: Light scattering results from glass fibre sample shown on a logarithmic scale for the power, plotted against scattering angle. The forward scattering (FS), side scattering (SS), and back scattering (BS) regions are shaded blue, red, and green respectively.

The most obvious inconsistency in these results is the missing data at around 90°, the power measured here was shown to read zero and, from the logarithmic scaling, was omitted. However, the overall shape of the scattering pattern was as expected from the investigations made into the literature.

3.5 Comparison of Results with Models

Comparisons of the measured scattering data and the data generated using different light scattering simulations are made within this section. The DT data will be the interference patterns of an aperture with the same widths as the diameters of the samples. The GLMT scattering will be generated using the infinitely long cylinder extension, as previously discussed¹⁷. The ADDA simulations used for comparison are made as representative as possible; the settings allowed for a beam width parameter that was set to 18 μm , as measured, and the length of the cylinder was set to extend just beyond this limit.

The minima of the scattering are found using a function included with MATLAB (MatLab – *islocalmin()*) and have been used as a method of comparison across the different data sets. The accompanying legends of the plots will abbreviate the different data as GLMT, ADDA, and DT as the Generalised Lorentz-Mie Theory (for infinite cylinders), the Amsterdam Discrete Dipole Approximation, and Diffraction Theory respectively. The data will be displayed here with a limit of 60° for the carbon sample, and 100° for the glass sample. This is to both exclude the unnecessary noise of the measured data and for a clearer visual comparison of the FS and SS

¹⁷ Contrary to the stated use of the finite length diffraction approximation GLMT at the end of Chapter 2, this chapter will not use this approximation due to the nature of the experiment.

sections where the measured data are more coherent with the model results – the complete plots of these results can be found in Appendix 7.2.

Further, the minima will also be compared. This is inspired from the introductory review of Section 3.1.2; a common method of measurement was counting fringes within a set angular range. The number of minima within a particular angle and their corresponding angular location will provide an easily quantifiable means of comparison. The reasoning for the choice of minima and not maxima is the anticipation for working with smaller diameter fibres and limitations of instruments, a first order maximum point will occur at a greater scattering angle than a first order minimum point. If an instrument measured forward scattering, the measurement of a minimum will be less restricted than that of the measurement of a maximum¹⁸. Fringe counting may also provide little information as a result of the same problem. Additionally, any saturation effects that may occur from improperly set up equipment will truncate the scattered light, and the angular location of the maximum point may not be accurately measured.

3.5.1 Carbon Fibre

3.5.1.1 Comparison with Simulations

Figure 3.13 shows the results of the scattering data from the carbon fibre sample, from the previous section, compared with the results of the various light scattering simulations. These results have been restricted to a scattering angle of up to 60° to display the more relevant data – full plots can be found in Appendix 7.2. A relatively good match is found between all data sets for most of the FS section but quickly diverges at different rates as the angle increases, some models more so than others.

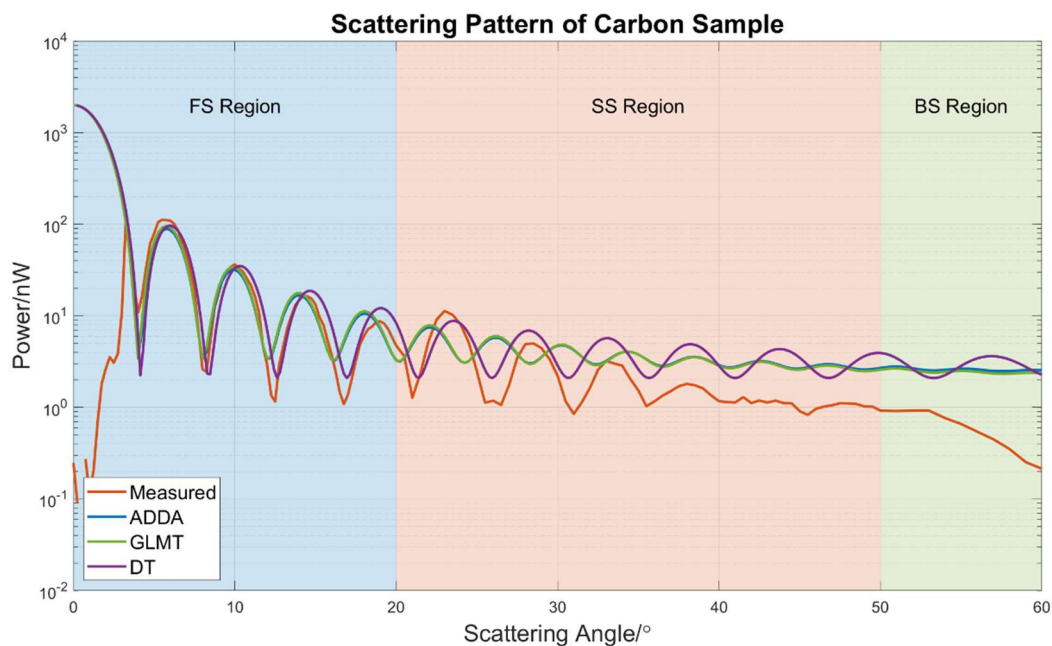


Figure 3.13: Scattering results of carbon fibre scattering experiment compared with results of models plotted on a logarithmic scale for the power against the scattering angle. The forward scattering (FS), side scattering (SS), and back scattering (BS) regions are shaded blue, red, and green respectively. The scattering angle is limited to 60°, but complete results are found in Appx. 7.2.

¹⁸ Noting that the central peak is not counted as a maximum fringe.

As a simple method of comparison, the minima can be used to help quantify how much the patterns diverge. An assessment of the agreement between the experimental data and the models is provided by determining the difference in angle for the first 13 orders of minima from the measured data, as shown in Figure 3.14, the first 5 of which are shown separately (right) to show the smaller differences of the ADDA and GLMT data.

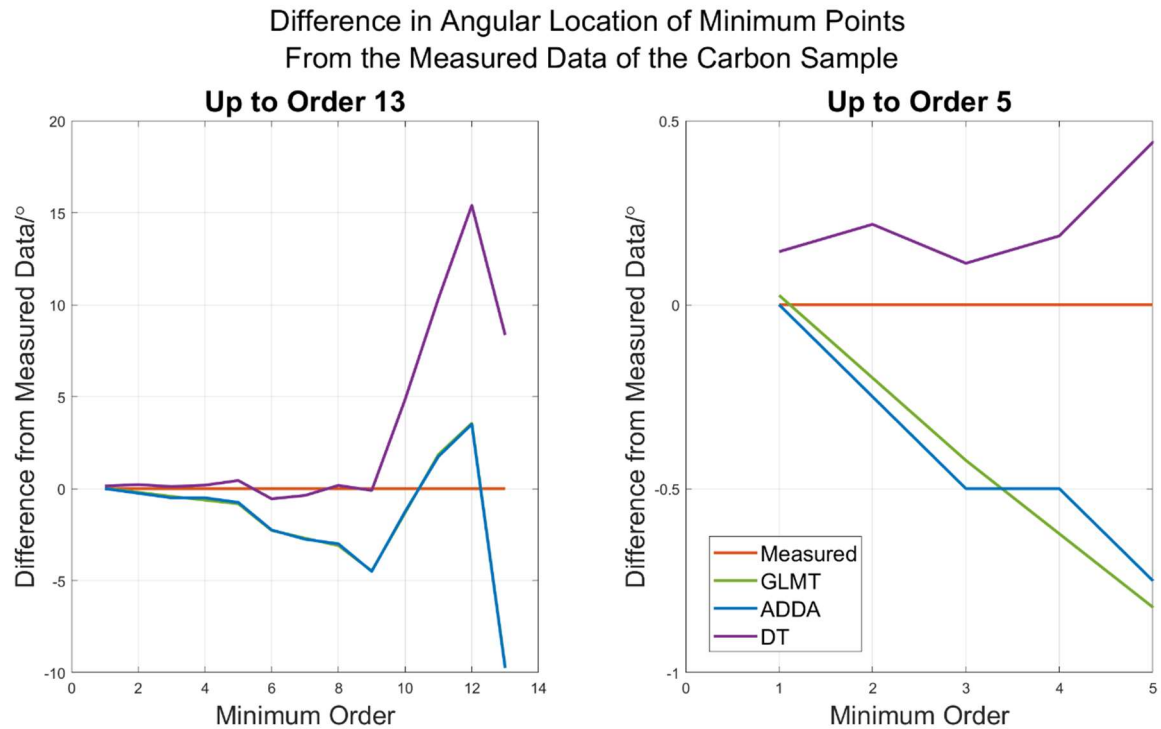


Figure 3.14: Differences in the angular locations, in comparison to the measured carbon fibre data (orange), found from the different models used. The right shows to the order of 13, the left 5. The Generalised Lorentz-Mie Theory (GLMT) is in green, the Amsterdam Discrete Dipole Approximation (ADDA) is in blue, and Diffraction Theory (DT) is in purple.

Again, this highlights the differences in the modelled scattering results compared to the measured data. Unsurprisingly, the diffraction theory results match reasonably well, to around the 9th minimum point, but diverges much faster for higher order minima. The ADDA and GLMT results, however, show a more dramatic divergence after the first minimum. Nonetheless, even for the difference found from the DT model (around 0.2° difference), this only corresponds to around a 0.3 μm (~4%) difference in diameter when considering the first minimum.

3.5.1.2 Limitations

Due to the high imaginary refractive index of the material, the resultant scattering pattern is dominated by diffraction effects. For the first nine minimum values the diffraction theory results matched reasonably well but diverged faster than the other simulations at a higher order minima. The closest match for the first minimum value is the ADDA simulation, which throughout matched well with the GLMT results, as expected from the comparisons made in Chapter 2. The actual refractive index of the material was unknown, an approximation was used and generated a reasonably good match to the measured data.

3.5.2 Glass Fibre

3.5.2.1 Refractive Index Problem

By comparing the measured data of the glass fibre scattering against that of the GLMT model, the prediction made regarding the refractive index in Section 3.2.2.3 was true. The ADDA was excluded from this initial process due to time restrictions but is included in Section 3.5.2.2 after a suitable refractive index was found. The combination of the low imaginary refractive index and the large size parameter of the fibre in the model would require around six hours for a single execution of ADDA on the UHHPC and in excess of 50 executions. As the results between ADDA and GLMT, shown briefly in Section 3.5.1.1 and in Chapter 2, produce very similar results and so only GLMT was used initially before any light scattering was computed using ADDA.

The scattering of the measured data and that of the GLMT model, using the refractive index for silicon-dioxide as previously discussed, does not match at all. The results are shown in Figure 3.15.

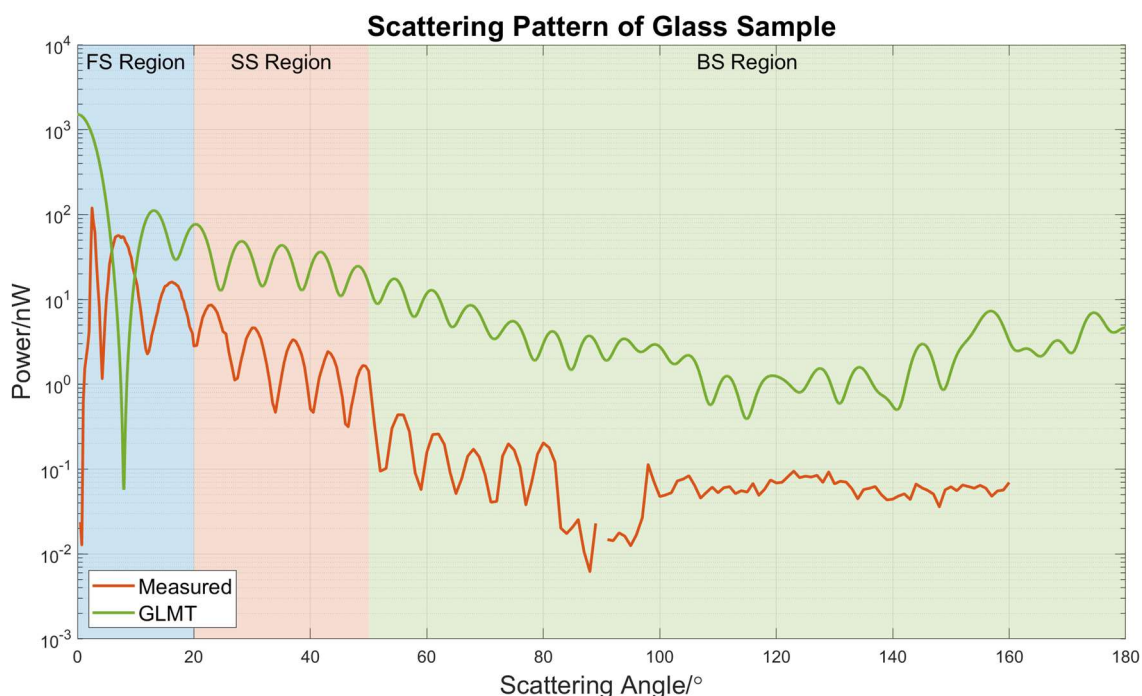


Figure 3.15: Scattering pattern of the measured data (orange), alongside the GLMT results of a cylinder of $5.2 \mu\text{m}$ diameter (green) with the refractive index of silicon-dioxide. The forward scattering (FS), side scattering (SS), and back scattering (BS) regions are shaded blue, red, and green respectively.

Further investigations were made and Kister et al. (2003) showed that the refractive index for bulk E-glass at a wavelength of 589.3 nm was 1.56. Unfortunately, the wavelength is different to that used throughout this investigation and there was no mention of imaginary refractive index but can be assumed to be very low.

From the poorly matched scattering patterns shown in Figure 3.15, along with the known fibre diameter and incident light wavelength, it is clear that the assumed refractive index is incorrect. Unfortunately, this lessens the validity of the purpose of this experiment, comparing real and modelled data. However, the same analysis undertaken for the carbon sample will still be done for this one regardless. A new refractive index was found using an iterative process matching patterns between the measured data and several GLMT-modelled patterns. First, 10201 sets of

GLMT-modelled patterns were generated, each with a diameter of $5.2\ \mu\text{m}$ and incident radiation wavelength of $532\ \text{nm}$. The imaginary refractive index was varied between $0.0i$ and $0.01i$ by increments of 0.0001 due to the likelihood that the absorption coefficient would be very small. For each of the different imaginary refractive indices, a set of GLMT-modelled scattering patterns were generated for different real refractive indices. These varied between 1.45 and 1.65 , as the real part was assumed to be around 1.56 , and these were varied in increments of 0.002 . As the minima seemed to be a good means of measurement, the average difference of the first four minima were taken for each 10201 patterns, shown in Figure 3.16 (left), the smallest difference was found at a refractive index of $1.532+0.0039i$ and the results are shown alongside the lab data (right).

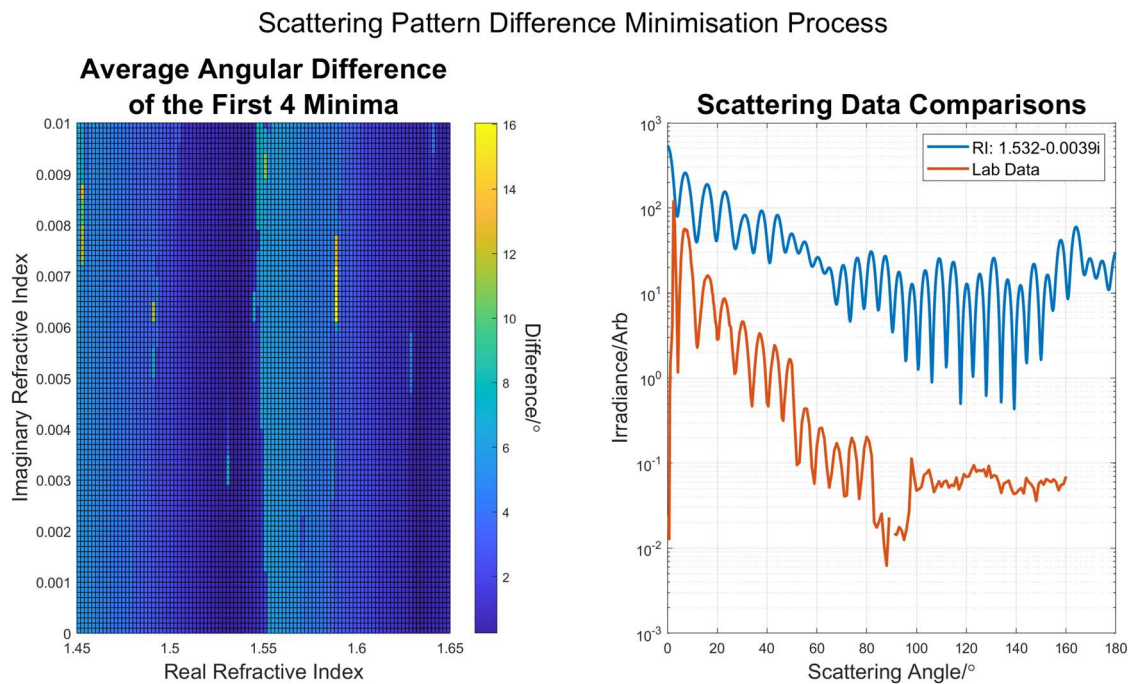


Figure 3.16: Refractive index finding process. Left shows a heatmap of the average difference of the first four minimum locations of the GLMT-modelled data, depending on refractive index. Right shows the comparison of the lab-collected data (orange) and the GLMT-modelled data of the refractive index with the smallest difference.

The match was still not as good as what was found for the carbon sample and so another process was conducted, similar to the previous. Several more, but not as many, scattering patterns were modelled in GLMT with varying refractive indices around $1.532+0.0039i$ to find a better visual fit. An example of 9 comparison plots for different refractive indices are shown in Figure 3.17 and a reasonable match was unexpectedly found to be $1.52+7e-7i$. This will be the refractive index used for the glass sample throughout this chapter and the results are shown in the following section. The anticipated refractive index of this material, however, was thought to have a higher real part than what was found by Kister et al. (2003). This is due to the general shape of the dispersion graphs for glass materials, when plotting the refractive index against the wavelength of the material, there is generally an increase in refractive index with a decrease in wavelength.

GLMT Iteration Examples to Find Appropriate Refractive Index

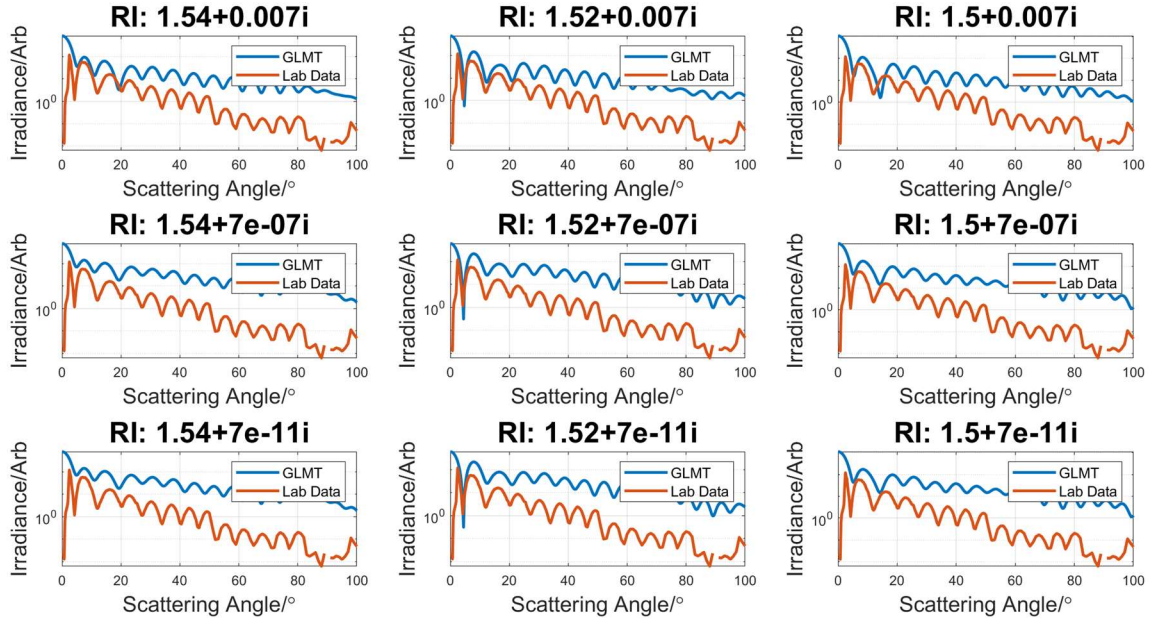


Figure 3.17: Examples of the visual comparisons made with the measured glass fibre scattering data (orange) and the GLMT modelled data (blue) to visually find an appropriate refractive index.

This process was not done for the carbon fibre sample in Section 3.5.1 as the assumed refractive index produced a reasonably good match with the experimental data, giving confidence that the assumed refractive index was correct.

3.5.2.2 Comparison with Simulations

Similar to the results for the carbon sample, the comparison plots for the glass sample are shown in Figure 3.18. The scattering angle has been restricted to 100° due to noise – full plots can be found in Appendix 7.2. The scattering comparisons show a much worse match than that of the carbon sample. Surprisingly, the ADDA and GLMT do not match as well with each other as they did for the previous sample or the comparisons made in Chapter 2. This may be the result of the GLMT-modelled data being of infinite length and the ADDA-modelled data having finite length, there may be additional interference from refraction and internal reflection caused by the finite length that has a slight impact on the resulting scattering patterns.

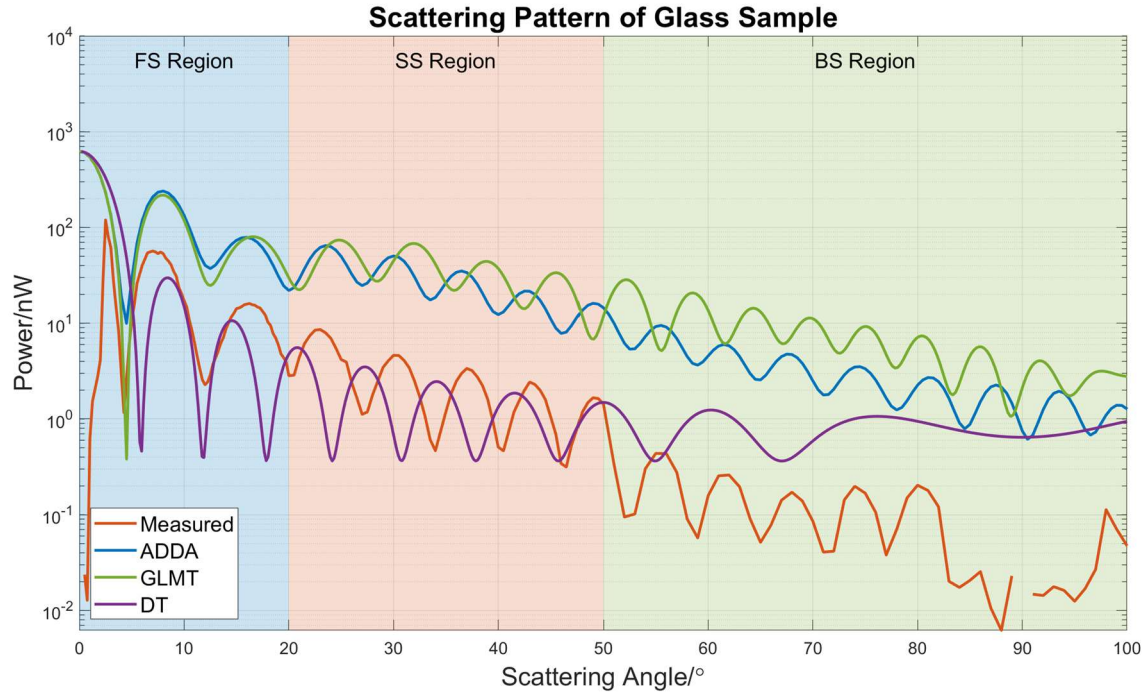


Figure 3.18: Scattering results of glass fibre scattering experiment compared with results of models plotted on a logarithmic scale for the power against the scattering angle. The forward scattering (FS), side scattering (SS), and back scattering (BS) regions are shaded blue, red, and green respectively. The scattering angle is limited to 100°, but complete results found in Appx. 7.2.

The relative differences in power along the scattering angles when comparing both GLMT and ADDA to the measured data were also surprising. After the close match found with the carbon fibre sample, a similar match was expected. However, this may be due to an imperfect match of the refractive index between the modelled data and the material itself. Unsurprisingly, the diffraction theory results are a much worse match as there will not be reflective and refractive effects considered in this much simpler model.

Figure 3.19 shows the angular difference from the measured data of the minimum points found from the different models for the first 13 orders (left) to highlight the level of divergence found for the DT results of a higher order number. The first 5 order minima are also shown (right), to show the, all be it lesser, divergence of the ADDA and GLMT results.

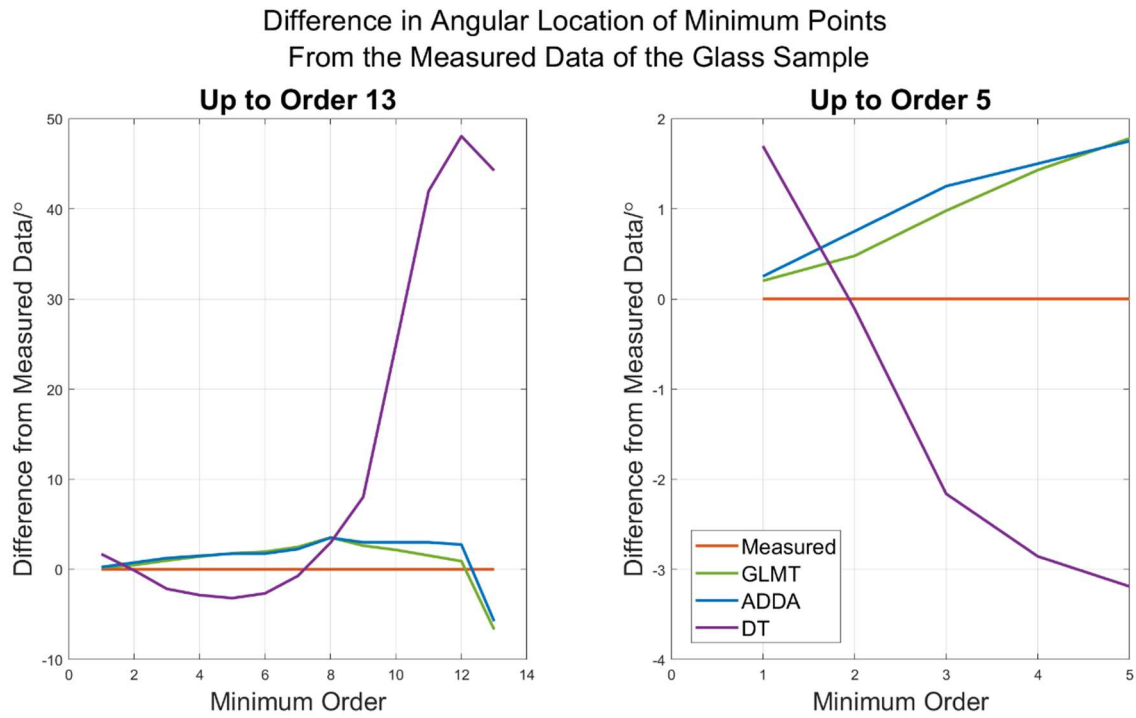


Figure 3.19: Differences in the angular locations, in comparison to the measured glass fibre data (orange), found from the different models used. The right shows to the order of 13, the left 5. The Generalised Lorentz-Mie Theory (GLMT) is in green, the Amsterdam Discrete Dipole Approximation (ADDA) is in blue, and Diffraction Theory (DT) is in purple.

The number of minimum points found in the $0^\circ - 40^\circ$ scattering angles of the measured data were consistent with those of the GLMT and ADDA models, but not with DT. This remained true up to the scattering angle of 80° , corresponding up to the 12th order minimum, before the measured scattering became noisy. The corresponding $0^\circ - 40^\circ$ angles of the minimum points matched quite well, up to the 6th order minimum, but quickly diverged with a greater scattering angle. With regards to the GLMT and ADDA models, there was a noticeable divergence of patterns as the scattering angle increased. This was unexpected as the results from the carbon fibre scattering showed a good match between GLMT and ADDA for the entire 180° scattering angle. The difference found in the first order minimum from the DT model is around 1.5° , corresponding to a diameter difference of $\sim 0.8 \mu\text{m}$ ($\sim 15\%$). This difference is much greater than the one found for the carbon fibre sample, but was expected due to the low absorption coefficient of the refractive index.

3.5.2.3 Limitations

Both the GLMT and ADDA results matched reasonably well with each other, as observed previously. Unsurprisingly, the DT results matched better with the carbon sample than the glass sample. When considering the first minimum point, however, the DT results did not show as good of a comparison to the measured data than that of the other models. GLMT showed a better first order minimum match for the glass sample, only a difference of 0.2° . ADDA showed an exact match for the carbon sample.

The irradiance levels found in the GLMT and ADDA modelled data are consistent with each other but not with the measured data, especially at larger scattering angles. This may have been a result of a faulty laser, poor calibration of the power levels, or the assumed refractive index.

3.6 Conclusions

The results of the experiments of this chapter show that diffraction theory is not adequate in matching the scattering patterns of a material with a low imaginary refractive index. With the high-refractive index carbon fibre sample, however, this method seemed to work as well as, if not better than, the more sophisticated light scattering models, at least for low order minima. Why the GLMT and ADDA results were a worse match may be due to an inaccurate assumption of the materials' refractive index. When comparing the diffraction theory results to the glass sample scattering, however, it was obvious that this model would be completely unusable as a means of measurement.

The use of counting within a set scattering angle, be it minimum or maximum points as was used in some of the literature, may be a fairly accurate technique. However, the diameters of the fibres used here are much larger than the respirable fibre range, stated by the WHO. Smaller diameter fibres are expected to produce much fewer interference fringes, as demonstrated in Chapter 2, creating the possibility that a fringe-counting method may be inadequate for smaller diameter fibres. This method will also be limited to the angular range of any instrument used to measure the scattering.

The almost identical results of the GLMT and ADDA were to be expected from their comparison in Chapter 2. The power levels along the scattering angle of these models was a much poorer fit for the glass sample than the carbon compared with the measured data. However, the minima for the FS section of the GLMT and ADDA modelled data and measured data aligned reasonably well. Unfortunately, as the refractive index was altered to better fit the scattering for the glass sample, this has less validity in how representative the models used are to real data. The use of matching scattering patterns to determine refractive index when the diameter is known may be useful in assessing the material the fibre consists of. However, this process proved to be laborious and also required *a priori* information that would not be available without careful experimentation.

Several factors need to be considered in judging the validity of these experiments. The laser being used was a bit temperamental, when recording measurements there seemed to be an occasional fluctuation in power output. This mostly happened shortly after powering it on, a period of 15 minutes was usually used for it to warm up before commencing. Even with this warmup period the occasional fluctuation was noticed and may account for the difference in the irradiance values in the previous plots. As previously stated, the voltage measurements of the oscilloscope were averaged over a time period but there could have been a steady decline in power output if the laser was faulty. Additionally, the power meter used showed variations when measuring for the normalisation measurements. This is a fairly normal occurrence as the sensitive area of the meter does not have a constant sensitivity. The level of intensity being measured was towards the lower end of the calibration scale and so a judgement of a stable reading may have also been wrong. Nonetheless, the different sections of the measured data align well, this would not have been true if the power readings taken for each gain setting were misinterpreted.

What has been presented in this section shows that simulations of light scattering can be representative of measurements of real fibres. The cylindrical analogue used in light scattering models surpasses the accuracy of the diffraction theory results, as was expected from the comparisons in Chapter 2. For reasons not fully understood, the irradiance levels of the glass sample decreased in similarity to those of the modelled data as the scattering angle increased.

Fortunately, no evaluation of the scattering in this work relies on a comparison of both patterns and irradiance. The decrease in irradiance level similarity is unimportant when only analysing the patterns produced.

A prominent feature of these comparisons was the first minimum, not considering diffraction. This feature did not rely on the matching of irradiance levels and so any measurements taken of fibres may be independent of any settings imposed on the instrument, such as camera gain.

There can be many improvements made to this experiment if ever repeated. A more stable laser and regular measurements of power would increase the confidence of the scattering produced. For an improved measurement of the SS and BS sections, an increase in power of the laser instead of the gain of the PMT may provide more details that are not drowned out by noise. Finally, the automation of the system of measurement and rotation would be essential for the analysis of more samples. The interpretation of the results would be greatly improved and much more robust if there was a larger selection of fibres. A range of diameters and refractive indices would make for a much-improved investigation.

Unfortunately, the time required to measure additional samples, as mentioned previously, would end up being quite large. Each sample required around a days work in the separation, mounting, and alignment procedure due to the breakages and sensitivity of alignment, as mentioned in Section 3.3. The data collection is also a lengthy procedure, taking around two days. If a batch of different fibres were sourced or created to repeat and reinforce this experiment, then the implementation of an automated, synchronous system of measurement would be beneficial. This was not done for the two samples investigated as automating this would have taken longer than the manual readings.

The next chapter used the selected models, investigated here, to develop and test a measurement technique for fibres. Several series of data were modelled using the GLMT and ADDA models with varying input parameters, such as diameter and length, to analyse any changes made in the resulting scattering patterns. The measurable changes found then provided a means of measurement that was then tested using a Monte Carlo-based method.

4 Fibre Characterisation from Theoretical Light Scattering Patterns

“When light encounters a strong magical field it loses all sense of urgency. It slows right down.”

-Terry Pratchett, The Light Fantastic, 1986

4.1 Introduction

The purpose of the investigation in this chapter is to analyse the computationally modelled light scattering patterns of cylinders and how they are affected by any changes to their parameters. These parameters include diameter, length, refractive index, orientation, and a brief mention of naturally curved fibres. By varying a single parameter, any resulting effects found in the scattering pattern can be analysed and a possible method of measurement may be found. Following the results of Chapter 3; variations in the scattering patterns can be anticipated regarding both diameter and refractive index. What is not anticipated, however, is how the reduction in size from the diameters of samples in Chapter 3 to those that conform to the WHO regulations will affect these results for a “finite” length.

The first half of this chapter uses both Amsterdam Discrete Dipole Approximation (ADDA) and Generalised Lorenz-Mie Theory (GLMT)¹⁹ modelled scattering data (investigated in Chapters 2 and 3) to analyse any change in the resultant pattern when a single variable is changed. Identifying different features of the scattering patterns that change with the varying input parameters, possible systems of measurement and their limitations were found from different measurable changes in the resulting scattering patterns.

The second half of this chapter uses the measurable features of the scattering patterns, investigated in the first half, to test a method of measurement using a Monte Carlo-based process. Two sets of reference data were generated for the measurement of both the length and diameter of the cylinder independently and a third set of data was generated from pseudo-randomised input variables. The features of all three sets were measured²⁰ and the reference data sets were used to determine the length and diameter of the pseudo-randomised data using the forward scattering patterns. The measurements were then compared with the input variables to observe how effective these measurement techniques were.

4.2 Parameters Investigated

4.2.1 Diameter

4.2.1.1 Parameters Changed

From what was noticed of the scattering patterns, mentioned in Chapter 3 and 2; as the diameter of the cylinder, or width of the slit, was changed the resulting interference pattern was either stretched or compressed. This can be seen in the equation for the single slit width interference equation from Chapter 2 (Equation 2.3), where $m\lambda = d \sin \theta$. As the width of the

¹⁹ Specifically the finite length diffraction approximation of the GLMT for infinitely long cylinders.

²⁰ Throughout this chapter different features of the scattering patterns will be analysed and referred to as measurements.

slit increases, the distance of the diffraction pattern minima from the central peak decreases and vice versa. The refractive index also caused the resulting scattering to change. A series of modelled scattering data have been created where the diameter input parameter is altered. All other parameters have been fixed as a means of comparison; an Euler angle of (0, 90, 0), a length of 10 μm , a wavelength of 532 nm²¹ for the incident radiation, and a refractive index of 1.5+0.5i. The diameters of the cylinders were within a set range conforming to the World Health Organisation (WHO) definition of respirable fibres. No lower limit²² is stated by the WHO, however, the diameter range will start from 0.02 μm ; this diameter is around 1/5th of the wavelength and seemed a sensible place to start before having to consider Rayleigh scattering. The diameter was then increased in steps of 0.1 μm up to 3.02 μm with a fixed length of 10 μm . Examples of the 90° forward scattering for the diameters 0.02 μm , 0.72 μm , 1.52 μm , and 3.02 μm are shown in Figure 4.1 – green arrows are included to indicate the location of the minimum.

ADDA 90° Forward Scattering from 10 μm Long Cylinders
of Varying Diameters at Euler Angles of (0, 90, 0)

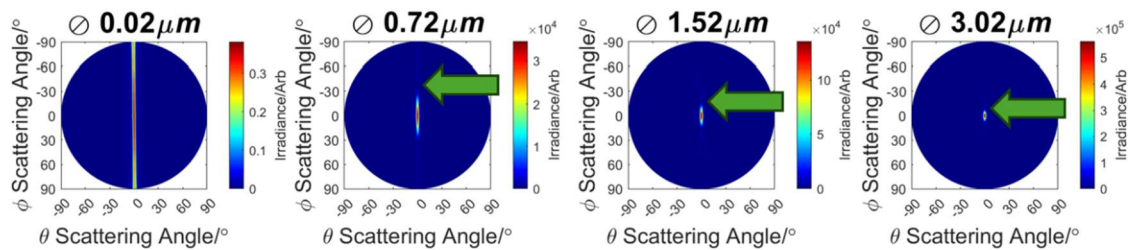


Figure 4.1: ADDA generated forward scattering examples of a 10 μm long cylinder of refractive index 1.5+0.5i with different diameters. The cylinders have an Euler angle of (0, 90, 0), and each image shows the scattering angle up to 90° of the forward direction. The green arrows indicate the minimum.

Similar results, shown in Figure 4.2, are found using the GLMT model. The square images of the GLMT scattering in Figure 4.2 are unlike the circular images of the ADDA model due to the generation process, explained in Chapter 2.

²¹ A wavelength of 532 nm for the incident radiation is used throughout this chapter unless otherwise stated.

²² Regarding the counting rules, a rough lower diameter limit for PCOM operators was found to be $\sim 0.25 \mu\text{m}$ – see Section 1.2.4.

GLMT 90° Forward Scattering from 10 μm Long Cylinders of Varying Diameters at Euler Angles of (0, 90, 0)

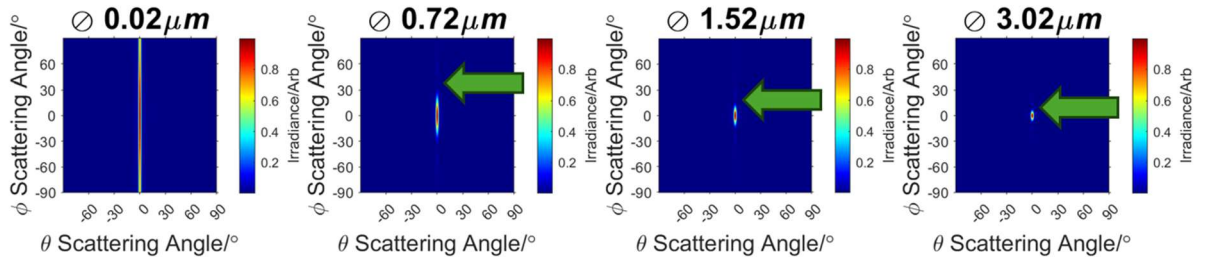


Figure 4.2: GLMT generated forward scattering examples of a 10 μm long cylinder approximation of refractive index $1.5+0.5i$ at different diameter inputs. The cylinders have an Euler angle of (0, 90, 0), and each image shows 90° of the forward scattering patterns. The green arrows indicate the minimum.

4.2.1.2 Changes in Measurement Metrics

What the green arrows of Figure 4.1 and Figure 4.2 indicate is the migration of the minimum towards the central point (the propagation direction of the incident light) with increasing diameter. To highlight this, Figure 4.3 shows the central vertical components²³ of the images in Figure 4.1 – the inverted spike in the centre of each plot is an artefact of how the scattering images are generated from the ADDA data.

Central Vertical Components of 10 μm Long Cylinders of Varying Diameters at Euler angles of (0, 90, 0)

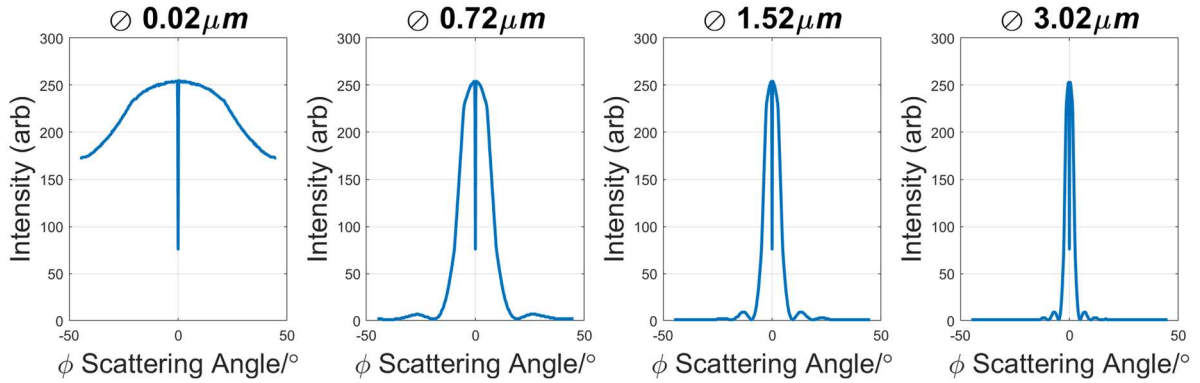


Figure 4.3: Central vertical components of the scattering patterns of 10 μm long cylinders of varying diameters, modelled in ADDA.

Measuring the angular location of the minimum and plotting it against the diameter of the cylinder is shown in Figure 4.4, which also includes the theoretical values of Equation 2.3 of single slit diffraction, showing the relationship between the minimum and the diameter.

²³ The column of pixels of the centre of the scattering image.

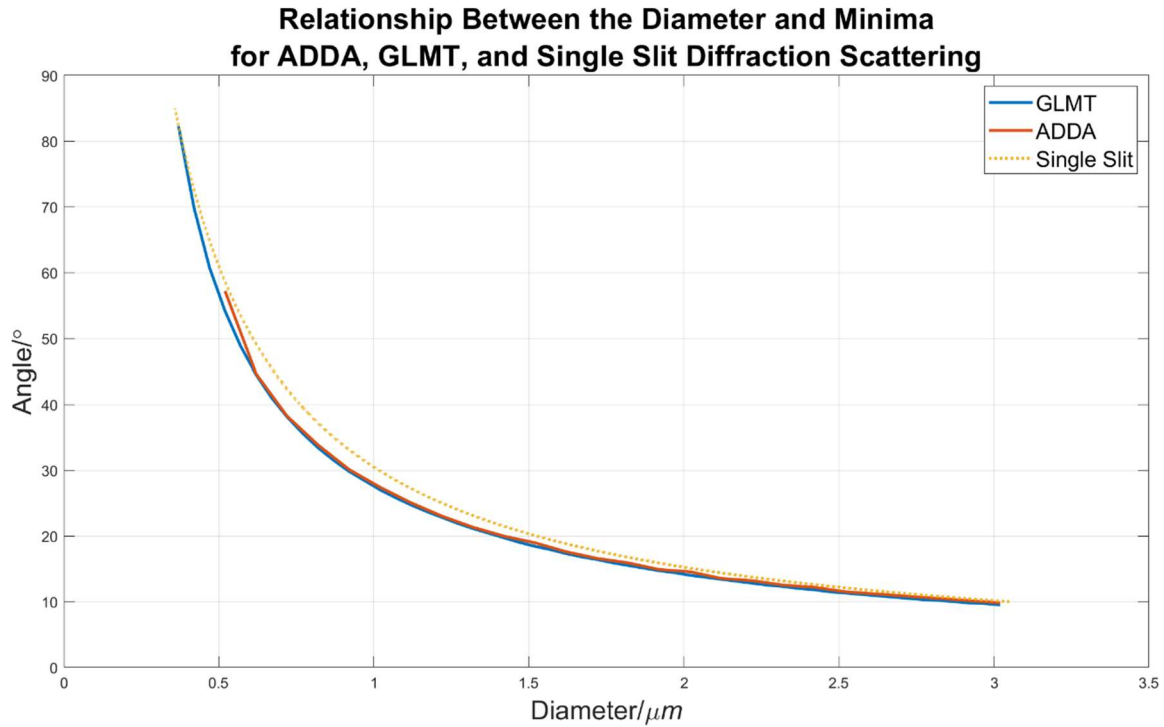


Figure 4.4: Minimum locations found from both GLMT (blue) and ADDA (orange) modelled data against the input diameter. A comparison of the theoretical results from Equation 2.3 are also included as a yellow dashed line.

The GLMT model found a minimum point for more of the smaller diameters than ADDA. This is due to the slightly noisy scattering pattern of ADDA, created when converting from a square matrix to a forward scattering image²⁴. Nonetheless, both measurements show good correlation, and the monotonic shape of the results suggests that identifying the location of an intensity minimum along the main scattering arc may be a useful method of measurement.

4.2.2 Length

4.2.2.1 Parameters Changed

Similarly, a series of scattering patterns were generated to model changes in cylinder length. A fixed diameter of 0.5 μm was used (selected to reduce the processing time required compared with objects of a larger size parameter) for length sizes within the range of 5 μm to 100 μm. The minimum length corresponds to the WHO definition of respirable fibres. The upper length limit is not explicitly stated in the WHO regulations, however, 100 μm seemed to be a reasonable size limit due to the beam cross-section of PPD2²⁵.

Figure 4.5 shows the forward 90° scattering of a 0.5 μm diameter cylinder with lengths of 5 μm, 10 μm, 15 μm, and 20 μm. These forward scattering patterns were generated using both ADDA (top row) and GLMT (bottom row). The bright band, typical of scattering from cylinders/fibres, decreases in width with increasing length. Again, this was an expected result from the investigations of Chapter 2 and broadly follows the theory for diffraction from a single slit, i.e., $m\lambda = d \sin \theta$. Visually, results for length inputs greater than 20 μm showed little difference.

²⁴ Explained in Section 2.5.2.

²⁵ Reported to be ~3 mm wide by ~80 μm deep – longer particles traversing the beam would either be rejected by ToF measurements or appear no different to those of that size.

ADDA and GLMT 90° Forward Scattering from 0.5 μm Diameter Cylinders of Varying Lengths at Euler Angles of (0, 90, 0)

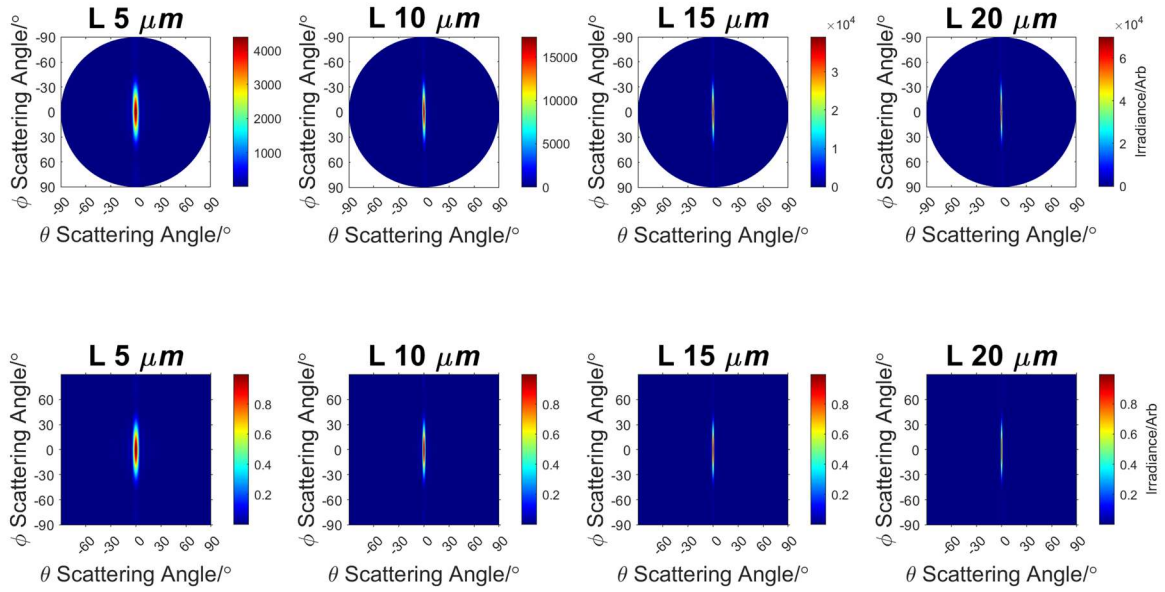


Figure 4.5: ADDA (top row) and GLMT (bottom row) generated forward scattering results of a cylinder of diameter 0.5 μm and refractive index 1.5+0.5i for a range of lengths. The cylinders have an Euler angle of (0, 90, 0), and each image shows 90° of the forward scattering patterns.

4.2.2.2 Changes in Measurement Metrics

Examples of the central horizontal components²⁶ of the forward 90° of scattering from the ADDA-modelled data (shown in Figure 4.5) are given in Figure 4.6.

Central Horizontal Components of 0.5 μm Diameter Cylinders of Varying Diameters at Euler angles of (0, 90, 0)

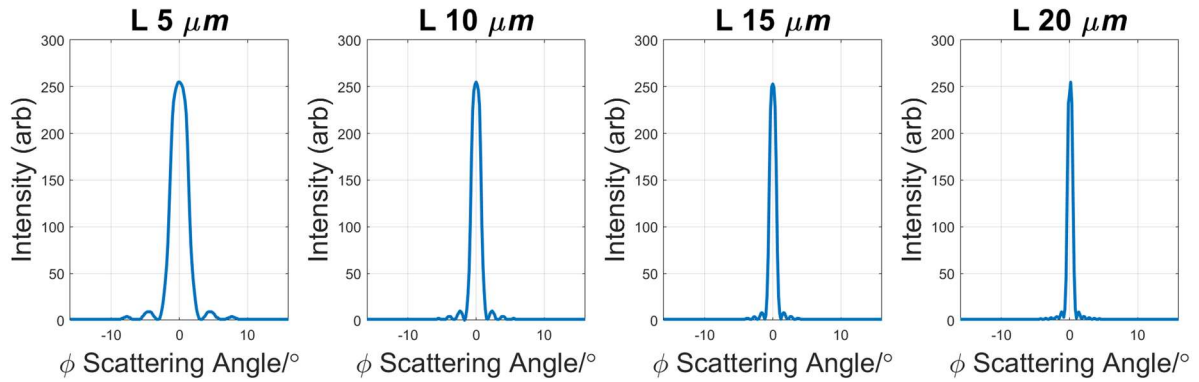


Figure 4.6: Central horizontal components of the scattering patterns of 10 μm long cylinders of varying diameters, modelled in ADDA.

Taking the full-width half-maximum (FWHM) of the central horizontal components of both the GLMT and ADDA for different length inputs is shown in Figure 4.7. Essentially, the GLMT results are those of diffraction theory due to the way the GLMT scattering was approximated for finite cylinder lengths. Figure 4.7 also includes the same measurements taken from the patterns produced from diffraction of a single slit to demonstrate this.

²⁶ The row of pixels in the centre of the scattering image.

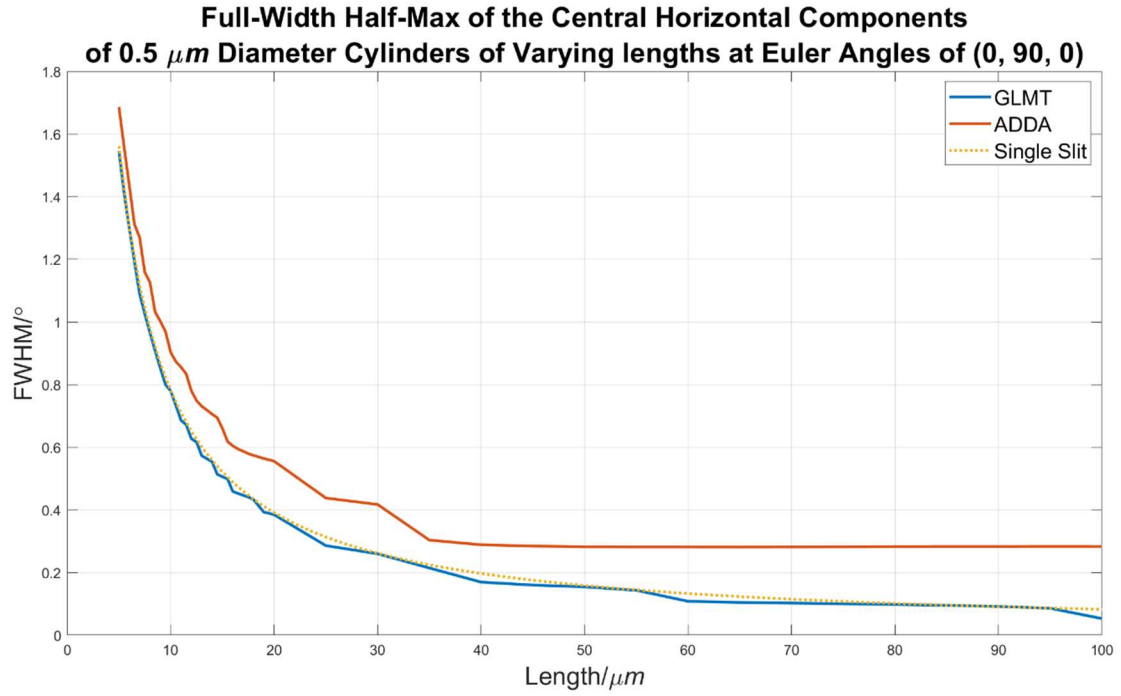


Figure 4.7: Full-width half-max measurements of the central horizontal components of both GLMT (blue) and ADDA (orange) against the input length parameters. A comparison of the theoretical results from Equation 2.3 are also included as a yellow dashed line.

These results show less of a match between the two models compared with the measurements used for the diameter, shown in Figure 4.4. This is due to the use of the finite length diffraction approximation used for the GLMT data; the results of Figure 4.4 considered diffraction, reflection, and refraction, whereas this approximation only uses diffraction. However, there is still a resemblance between the two models, but the ADDA results show the FWHM reaching an asymptotic state sooner than GLMT, at around 40 μm long.

4.2.3 Length/Diameter Dependence

4.2.3.1 Parameters Changed

To check there is no dependence between the features identified in the two previous sections, the effects of simultaneously changing both length and diameter are now analysed to monitor any effect one changing variable has on the measurable feature of the other. The FWHM of the length was measured for different diameters and the minimum has been monitored for different length values. Significant differences in these measurements may indicate some co-dependence. The measurements will only be monitored for the ADDA modelled data as the GLMT results are completely independent due to the way in which the scattering is generated. Explained in Chapter 2, the scattering pattern for the GLMT modelled data is a vector outer product of two arrays and therefore a change in one array will not affect the other.

The diameter that has been used as examples for the changing lengths in the previous section have been producing a minimum of around 50° . Unfortunately, the pattern produced is too shallow, causing the algorithm used to find the local minimum to fail, demonstrated in the example shown in Figure 4.8 (right-hand side). To compensate for this, a new set of modelled data was generated with a fixed diameter value of $1 \mu\text{m}$. The more prominent interference patterns, as seen in Figure 4.8 (left-hand side), will contribute for a better comparison of any

interdependence of the FWHM and minimum measurements. This limitation in locating the minimum will be addressed in Section 4.3.1.4.

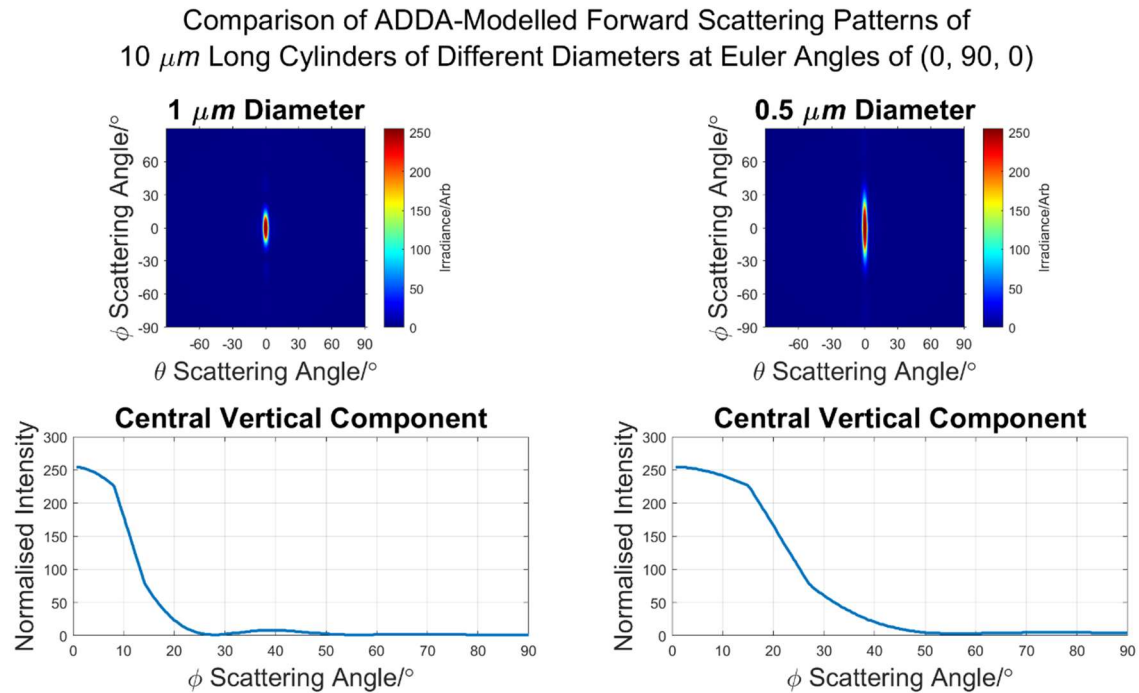


Figure 4.8: ADDA-Modelled forward scattering examples of 10 μm long cylinders (top) for diameters of 1 μm (right) and 0.5 μm (left) to demonstrate the prominence of the minimum points in their central vertical components (bottom). The refractive index of the cylinders are $1.5 + 0.5i$.

4.2.3.2 Changes in Measurement Metrics

To determine how dependent the FWHM measurements are on the diameter of the cylinder, a series of scattering images from 10 μm long cylinders of varying diameters were modelled by ADDA. Each image was used to measure the FWHM and Figure 4.9 (left hand side) shows these measurements plotted against the changing diameter inputs. Using the diffraction results from a single slit of width 10 μm at a wavelength of 532 nm, the FWHM measurement is expected to be around 0.93°.

Similarly, to determine how dependent the minimum measurements are on the length of a cylinder, a series of scattering images from 1 μm diameter cylinders of varying lengths were also modelled by ADDA. Each image was used to measure the minimum and Figure 4.9 (right-hand side) shows these measurements plotted against the changing length inputs. Using the diffraction results from a single slit of width 1 μm and a wavelength of 532 nm, the minimum was expected to be around 40° ($\theta = \sin^{-1}(\lambda/d) = 39.42^\circ$). However, this value was measured to be around 28°. This is likely due to the additional interactions caused by reflection and refraction and not considered by Equation 2.3. The results of both of these tests are shown in Figure 4.9.

ADDA Measurement Dependencies

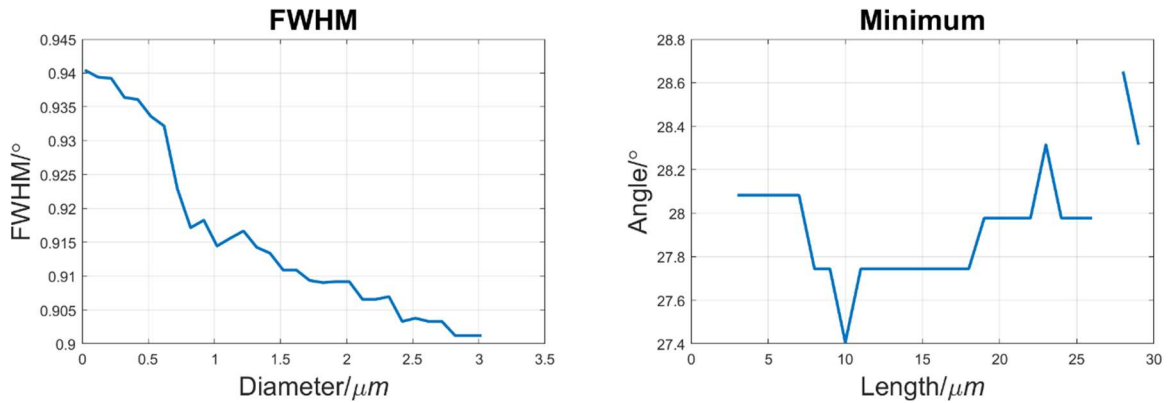


Figure 4.9: Full-width half maximum measurements of the central horizontal component of the forward scattering pattern of a 10 μm long cylinder modelled in ADDA (left) at a range of diameters. Right shows the minimum measurements of a 1 μm diameter cylinder, modelled in ADDA with a range of different lengths.

By cross-referencing the FWHM measurement results, shown in Figure 4.9, with those shown in Figure 4.7, the difference in length equates to around 0.2 μm . The difference in diameter equates to around 0.1 μm . The results of this section demonstrate that a difference in FWHM is found when varying the diameter and similarly, a change in the minimum is also found with varying length. Fortunately, the variation found for either measurement is negligible.

4.2.4 Orientation Dependence

4.2.4.1 Parameters Changed

The orientation of a fibre relative to the incident radiation, is an important factor in the instrumentation discussed in Chapter 2. Modelling scattering patterns of cylinders at different orientations demonstrates the difference in the scattering results.

Rotation of a homogeneous, axisymmetric object (in this case, a cylinder) about the axis of symmetry will result in no change in the scattered light. Rotating about either of the two other axes will affect the resulting scattering pattern. Any rotation of the cylinder about the axis of the propagation direction will result in the scattering pattern rotating by the same angle. An Euler angle²⁷ of (0, 90, 0) will produce the scattering patterns seen hitherto, however, an Euler angle of (α , 90, 0) will produce the same scattering pattern, rotated by α° by an axis orthogonal to the plane of the page. Examples are shown in Figure 4.10.

²⁷ See end of section for clarification examples or refer to Section 1.5.5 for further explanation.

ADDA 90° Forward Scattering from 0.5 μm Diameter
 $\times$ 10 μm Cylinders at Euler Angles of $(\alpha, 90, 0)$

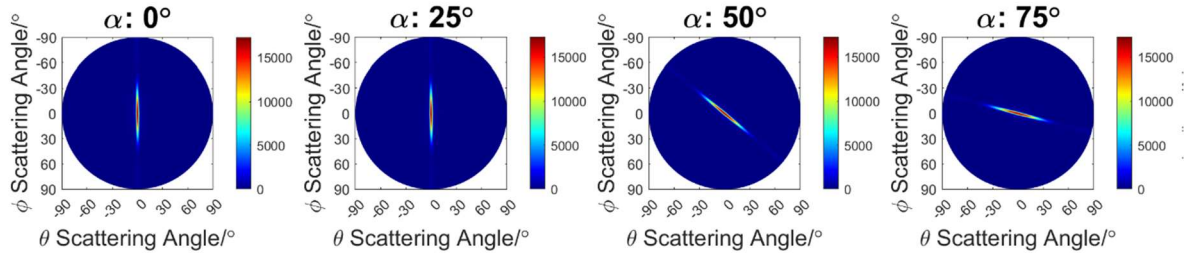


Figure 4.10: ADDA 90° forward scattering results of a 0.5 μm diameter by 10 μm long cylinder of refractive index $1.5+0.5i$ at different α Euler angles for $(\alpha, 90, 0)$.

Changing the β Euler angle (i.e., the major axis of the cylinder is no longer aligned with a plane that is perpendicular to the propagation direction of the incident light)²⁸, will cause more significant changes in the resultant scattering. Below shows examples modelled using ADDA of a 0.5 μm diameter by 10 μm long cylinder of refractive index $1.5+0.5i$ at Euler angles of $(0, 25, 0)$, $(0, 45, 0)$, $(0, 75, 0)$, and $(0, 85, 0)$.

ADDA 90° Forward Scattering from 0.5 μm Diameter
 $\times$ 10 μm Cylinders at Euler Angles of $(0, \beta, 0)$

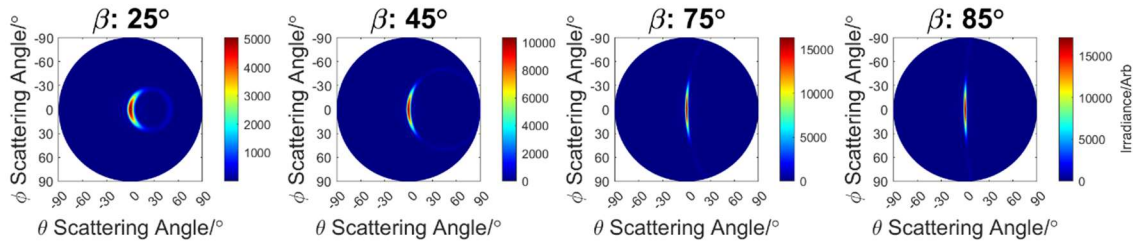


Figure 4.11: ADDA 90° forward scattering results of a 0.5 μm diameter by 10 μm long cylinder of refractive index $1.5+0.5i$ at different β Euler angles for $(0, \beta, 0)$.

For GLMT, however, the resulting scattering patterns at different orientations are not representative of reality due to the method in which the length is approximated²⁹. Therefore, when comparing the profile of the scattering arcs taken from the central vertical components, as shown in Figure 4.12, the patterns do not match at all.

²⁸ More in depth explanation of orientation found in Chapter 1 and Section 4.2.4.2.

²⁹ See Section 2.3.2.3

GLMT/ADDA 90° Forward Scattering Comparison of 0.5 μm Diameter $\times$ 10 μm Long Cylinders

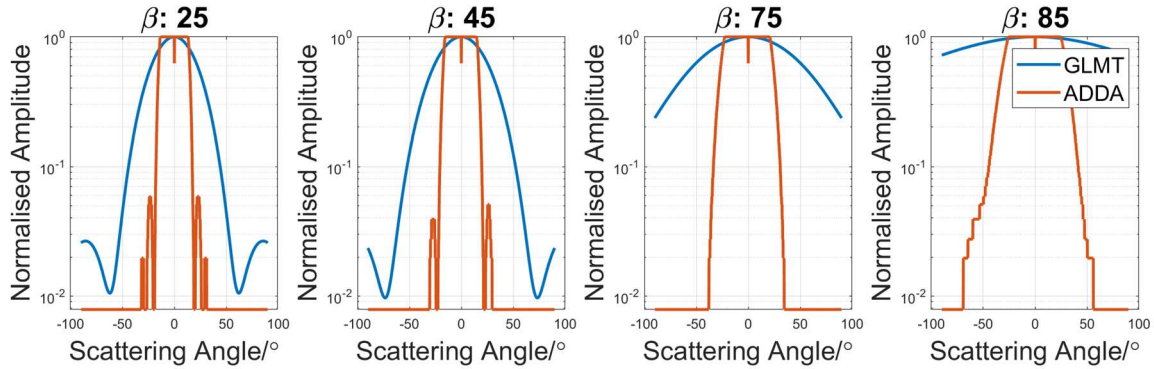


Figure 4.12: Comparison of central vertical components of GLMT (blue) and ADDA (orange) of a 0.5 μm diameter by 10 μm long cylinder at different β Euler angles.

4.2.4.2 Orientation Clarification

For further explanation of the orientation of the fibres, an accompanying set of examples are shown in Figure 4.13, in addition to the explanation in Section 1.5.5.

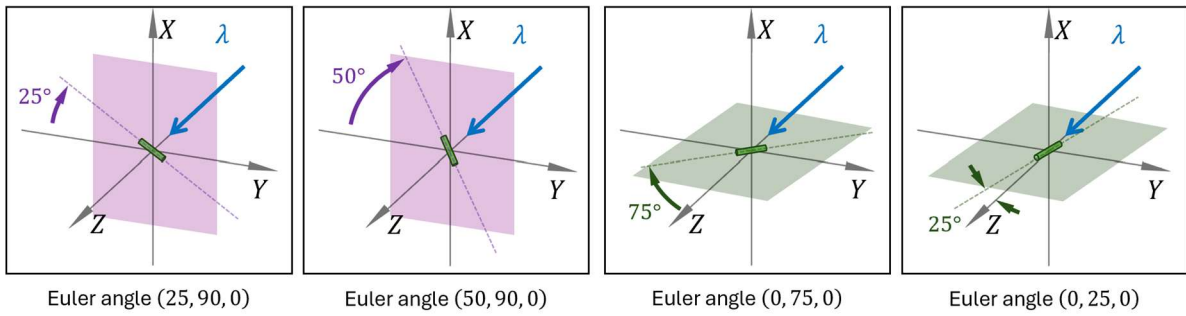


Figure 4.13: Examples of cylinder orientation using Euler angles. The two left images show a change in the α angle, with β and γ set at 90° and 0° respectively, corresponding to a rotation in the $X - Y$ plane (magenta). The two right images show a change in the β angle, with α and γ both set at 0°, corresponding to a rotation in the $Z - Y$ plane (green).

Corresponding to the images shown in Figure 4.10, Figure 4.13 (left-hand side) shows two examples of the orientation of the cylinder at Euler angles of (25, 90, 0) and (50, 90, 0)³⁰. The change in the α angles, with β and γ set at 90° and 0° respectively, rotates the cylinder in the $X - Y$ plane (magenta). Corresponding to the images shown in Figure 4.11, Figure 4.13 (right-hand side) shows two examples of the orientation of the cylinder at Euler angles of (0, 75, 0) and (0, 25, 0)³¹. The change in the β angles, with α and γ set to 0°, rotates the cylinder in the $Z - Y$ plane (green).

4.2.4.3 Changes in Measurement Metrics

Using ADDA modelled data, a series of scattering patterns from a 0.5 μm diameter by 10 μm long cylinder were made with a β angle varying from 0° to 90° with both α and γ set to 0°. Fitting a circle to the curvature of the bright band gives a relationship between the β angle orientation and the radius of curvature of that circle.

³⁰ Two centre images of Figure 4.10.

³¹ Left and one in from right images of Figure 4.11.

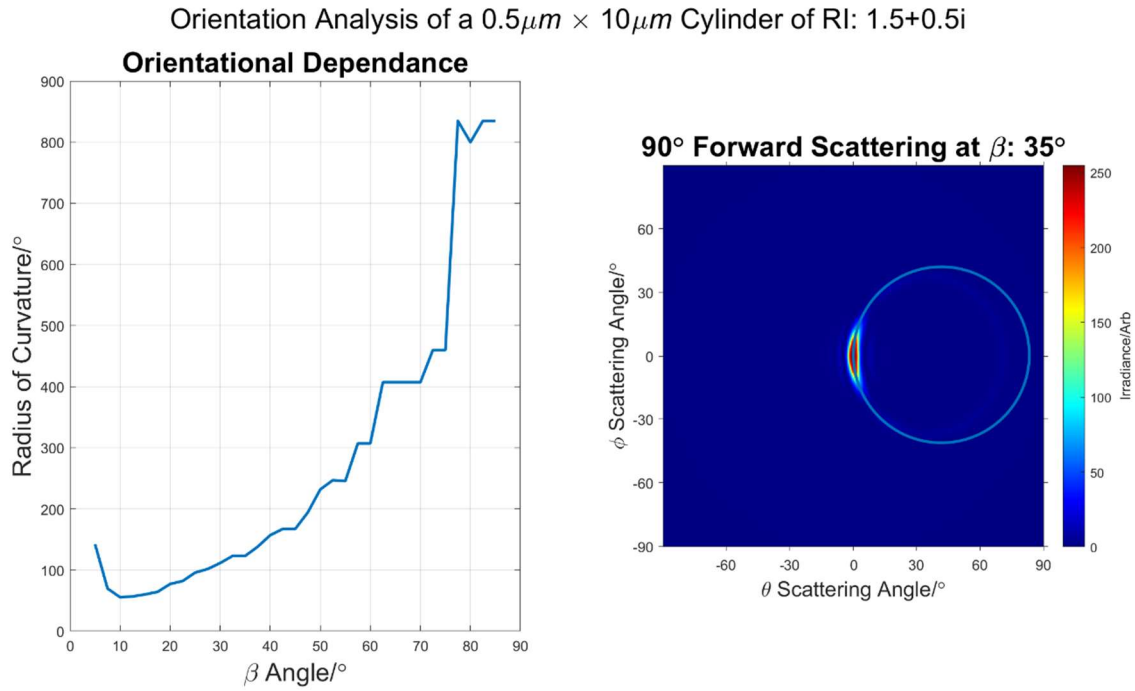


Figure 4.14: Relationship of the radius of curvature fitted to the resulting 90° forward scattering results of ADDA from a $0.5\mu\text{m}$ diameter by $10\mu\text{m}$ long cylinder of refractive index $1.5+0.5i$ for different β angles (left). Right shows an example of the 90° forward scattering including the fitted circle.

From the example shown in Figure 4.14 (right), the circle is not perfectly fitted to the bright band all the way around but shows a reasonably accurate fit to the brighter parts. The curve of the scattering pattern is not circular due to the distortion created when displaying the pattern as a 2D image and not projected onto a sphere. However, it is good enough to demonstrate the relationship between the change in β angle orientation and the resulting scattering pattern. An explanation into how the curve is fitted can be found in Appendix 7.4.1.3.

The relationship between the radius of curvature and the β angle, shown in Figure 4.14 (left) shows an exponential curve that approaches infinity towards a β angle of 90° where the bright band should be a straight line. The non-monotonic behaviour seen at the smaller angles is a result of the algorithm used to fit the circle. Fortunately, β values of anything less than $\sim 15^\circ$ result in scattering patterns that have no apparent features typical of fibres and look more like the scattering from a sphere or droplet. The alignment of the cylinder with the incident radiation results in a circular shape, this causes the scattering patterns to resemble Airy disks³². Figure 4.15 shows examples of the circle fitting for the smaller angles where the “ring” pattern, caused by a high aspect ratio particle at a non-normal incidence angle, is only discernible at around 12.5° , explaining the non-monotonicity of the smaller angles in Figure 4.14. Nonetheless, these results demonstrate the possibility of the orientational measurement of the particle using this technique on the scattering patterns produced.

³² Concentric ring scattering patterns produced by spherical objects or circular apertures.

Circle Fitting Examples

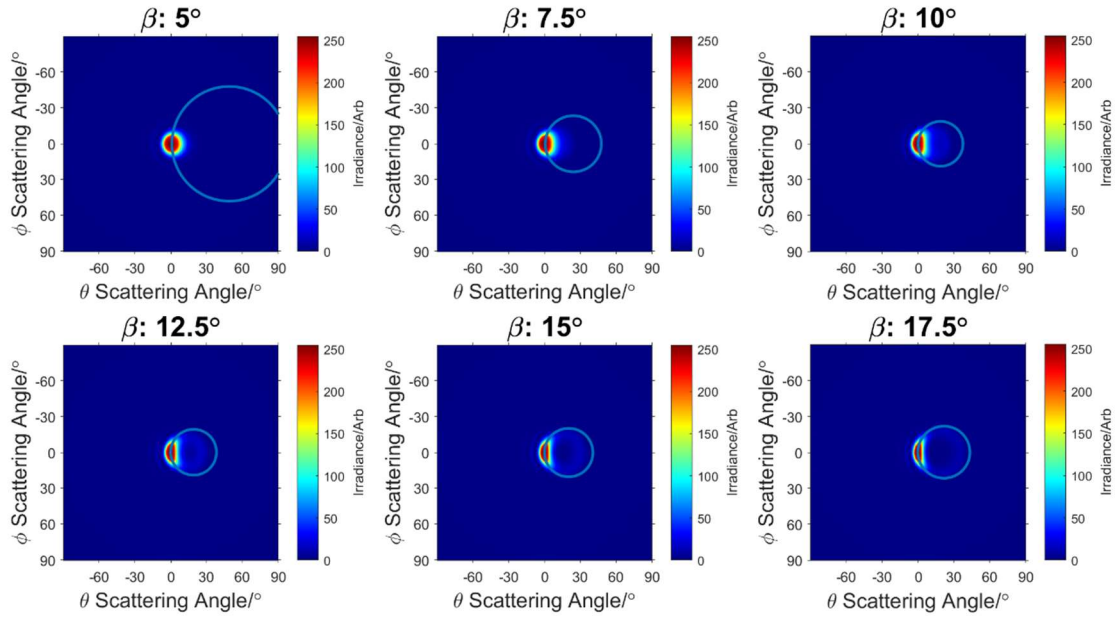


Figure 4.15: Examples of the circle fitting for orientation measurements at small angles to explain the non-monotonic results of Figure 4.14.

Monitoring the FWHM and minimum, associated with the length and diameter respectively, when varying the orientation of the cylinder is also necessary in identifying the limitations of measurement. The results of the FWHM and minimum, depending on the β angle are shown in Figure 4.16. The following measurements have been administered using a cylinder of diameter $1\ \mu\text{m}$ by $10\ \mu\text{m}$ long to ameliorate the lack of minimum points found, as mentioned in Section 4.2.2.1.

Orientational Measurement Dependencies

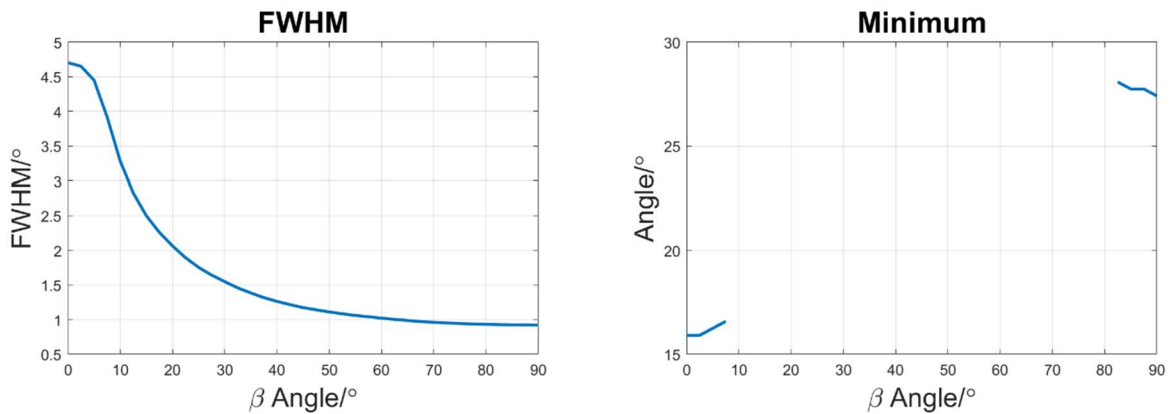


Figure 4.16: Full-width half-maximum measurements of the central horizontal component (left) and the minimum of the central vertical component (right) of the 90° forward scattering of a $1\ \mu\text{m}$ diameter by $10\ \mu\text{m}$ long cylinder modelled in ADDA.

The results in Figure 4.16 show the differences in the FWHM and minimum measurements that can be observed depending on the β Euler angle orientation. For the FWHM, relating to length, as the β approaches 90° the FWHM measurement asymptotes to a value of around 1, starting after around 60° . This demonstrates that the orientational dependence on the measurements may only be significant beyond a limit. For example, limiting the orientation between the angles

of 60° and 90° is shown in Figure 4.17 and the FWHM value only differs by 0.4° over a β angle orientation of 30° . The results of Figure 4.16 (right) show some minimum points found at very small values of β , this is the result of the cylinder being mostly parallel with the incident light and creating Airy disk patterns and a minimum found as a result. The absence of data between 10° and 80° are the result of no minimum being found by the algorithm, however, beyond 80° the minima are found to be at around 28° , as expected for a diameter of this size.

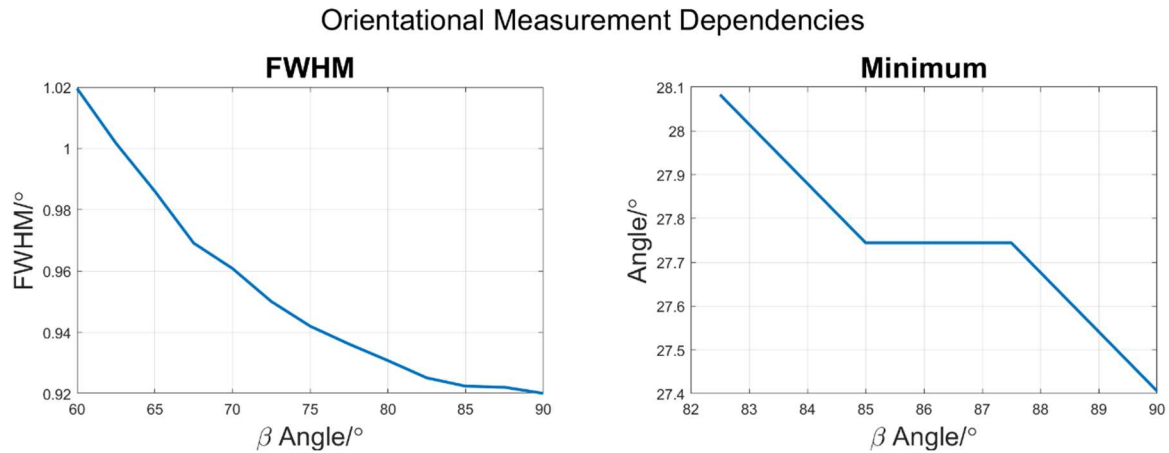


Figure 4.17: Results shown in Figure 4.16 but limited to β angles between 60° and 90° .

Now, after limiting the orientation between 60° and 90° , the FWHM result deviation only corresponds to a difference in a length of around $0.2 \mu\text{m}$ and the diameter $0.025 \mu\text{m}$. This shows that the orientational dependence of measurement is only significant beyond a particular angular limit and, as discussed in Chapter 1, the orientation of fibres can be reasonably controlled within an airflow.

4.2.5 Refractive Index

4.2.5.1 Parameters Changed

To investigate how refractive index affects the resulting scattering patterns, a series of modelled data was generated. Cylinders of $0.5 \mu\text{m}$ diameter and $10 \mu\text{m}$ long were used in ADDA and the corresponding approximations for GLMT. The first set of data varied the real component of the refractive index from 1 to 2, the second varied the imaginary component from 0 to 1. Examples of the 90° forward scattering from the ADDA model (top row) and GLMT model (bottom row), with varying values of a real imaginary refractive index are shown in Figure 4.18.

ADDA and GLMT 90° Forward Scattering from 0.5 μm Diameter $\times$ 10 μm Long Cylinders
of Varying Real Refractive Index at Euler Angles of (0, 90, 0)

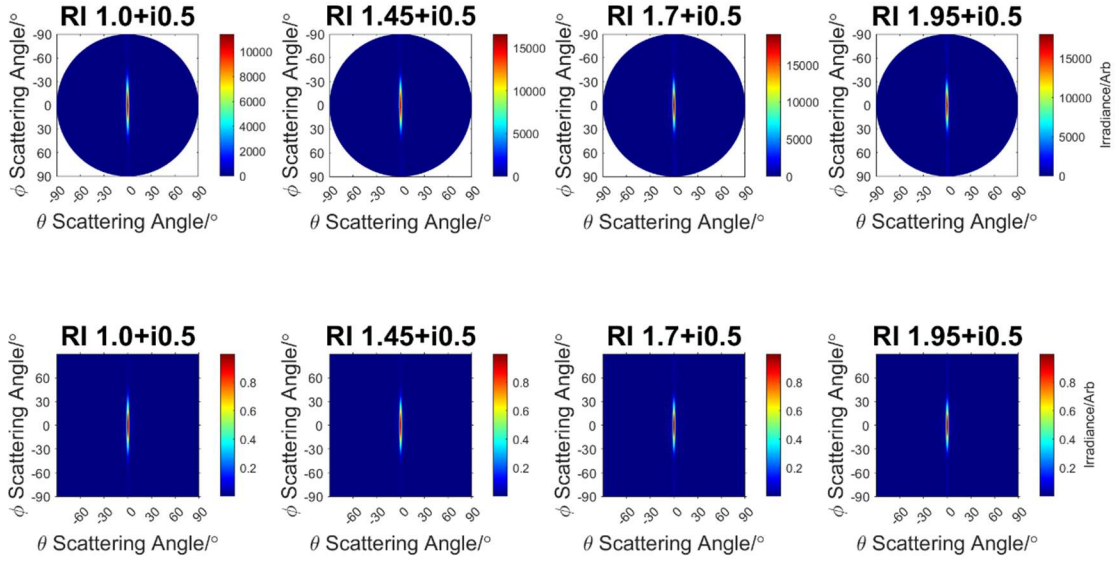


Figure 4.18: ADDA (top row) and GLMT (bottom row) 90° forward scattering results of 0.5 μm diameter by 10 μm long cylinders of different real refractive index.

Changing the imaginary component of the refractive index with a fixed real value of 1.5 are shown in Figure 4.19 for the ADDA model (top row) and the GLMT model (bottom row).

ADDA and GLMT 90° Forward Scattering from 0.5 μm Diameter $\times$ 10 μm Long Cylinders
of Varying Imaginary Refractive Index at Euler Angles of (0, 90, 0)

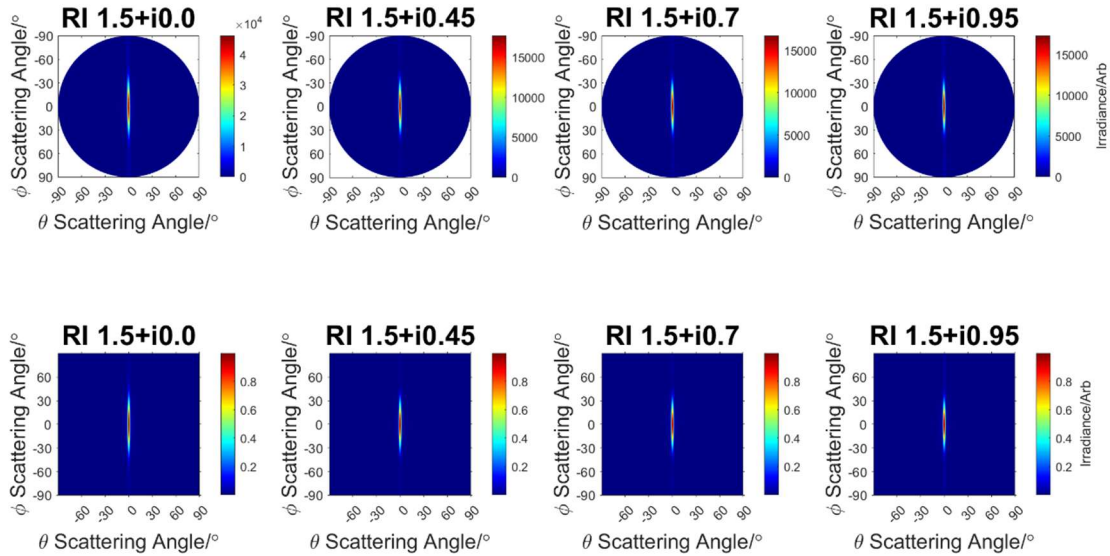


Figure 4.19: ADDA (top row) and GLMT (bottom row) 90° forward scattering results of 0.5 μm diameter by 10 μm long cylinders of different imaginary refractive index.

4.2.5.2 Changes in Measurement Metrics

As the example results shown in the previous section have no striking dissimilarities the FWHM and minimum measurements will be repeated and compared. Any difference in the minimum or the FWHM will indicate how dependent the resulting scattering patterns may be on the refractive index. Figure 4.20 shows the measurements taken from the 90° forward scattering of a

0.5 μm diameter cylinder of length 10 μm , with the FWHM (left), and minimum (right) found when varying the real refractive index and a fixed imaginary refractive index of 0.4.

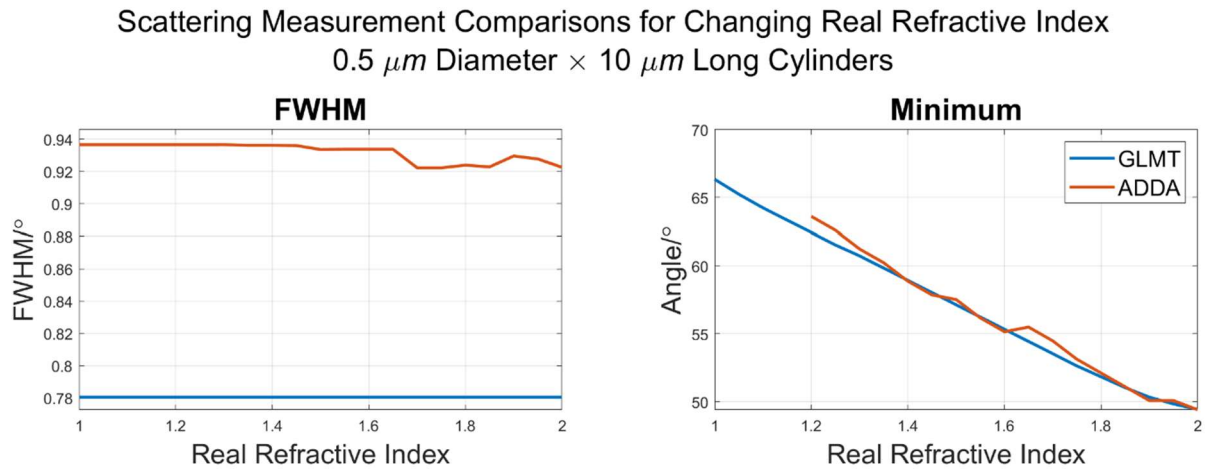


Figure 4.20: FWHM (left) and minimum (right) measurements found for GLMT and ADDA from the 90° forward scattering from a 0.5 μm diameter by 10 μm long cylinder for different real refractive indices.

The GLMT results for the FWHM measurement are all the same due to the finite length diffraction approximation³³. The FWHM of the ADDA scattering data shows a small fluctuation for the higher real parts of the refractive index. The difference in FWHM measurements shown in Figure 4.20 (left) is equivalent to an error in length measurement of around $\pm 0.2 \mu\text{m}$. The difference in the minimum measurements, in Figure 4.20 (right), for both models is equivalent to an error in diameter measurement of around $\pm 0.1 \mu\text{m}$ when examining Figure 4.4. Similarly, the same results obtained from altering the imaginary part of the refractive index, with a fixed real value of 1.5, is shown in Figure 4.21.

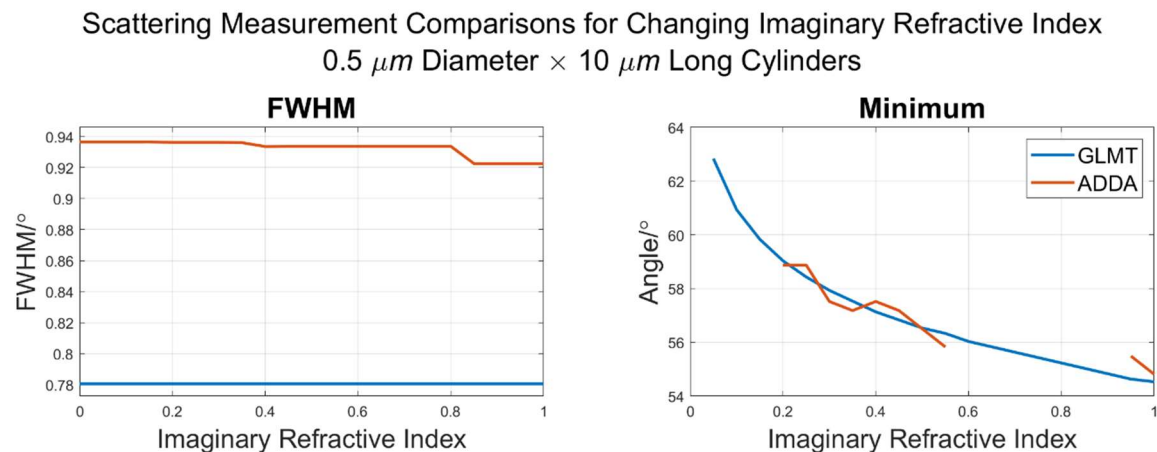


Figure 4.21: FWHM (left) and minimum (right) measurements found for GLMT and ADDA from the 90° forward scattering from a 0.5 μm diameter by 10 μm long cylinder for different imaginary refractive indices.

The results are very similar to those shown in Figure 4.20, however, the minimum shows a slight difference, but again is only equivalent to an error of around $\pm 0.1 \mu\text{m}$ in diameter measurement. The decrease in the angle is more of a curve for the GLMT results. The differences in the measurements, even including the outlier of the FWHM results, is less than those of the change in real refractive index and so will correspond to a smaller change in measured length or

³³ See Section 2.3.

diameter. The missing ADDA data shown in both Figure 4.20 and Figure 4.21 are the result of the diameter of the cylinder. It was set at $0.5\ \mu\text{m}$ to reduce processing time but also reduces the ability of the algorithm to locate a minimum point (as mentioned in Section 4.2.3.1), this coupled with the noise introduced by the conversion of the raw ADDA data to an image and the variation in input parameters (i.e., refractive index), some minima were missed.

To examine the effect the refractive index has on the measurements for different diameters, additional sets of data were modelled using both ADDA and GLMT, the results are shown in Figure 4.22. Due to time restrictions, only diameters of $0.25\ \mu\text{m}$, $0.5\ \mu\text{m}$, $1\ \mu\text{m}$, $1.5\ \mu\text{m}$, $2\ \mu\text{m}$, and $2.5\ \mu\text{m}$ were generated with four different real refractive indices and four imaginary refractive indices. As before, the real part was set to 1.5 when varying the imaginary part between 0 and 1 ($m = 1.5 + im_i$) and the imaginary part was set to 0.5 when varying the real part between 1 and 2 ($m = m_r + i0.5$). An additional set³⁴ for observing changes in measurements for varying real refractive index with an imaginary part of 0 ($m = m_r + i0.0$)³⁵. Unexpectedly, the FWHM measurements for the GLMT-modelled data (Figure 4.22, bottom right) had no variation – due to the finite length approximation, each diffraction pattern is the same and so no variation is observed. The variation shown in the FWHM for the ADDA-modelled data (top right) is only small ($\sim 0.04^\circ$ overall) and, according to Figure 4.7, is equivalent to a $\pm 0.75\ \mu\text{m}$ error in length measurement.

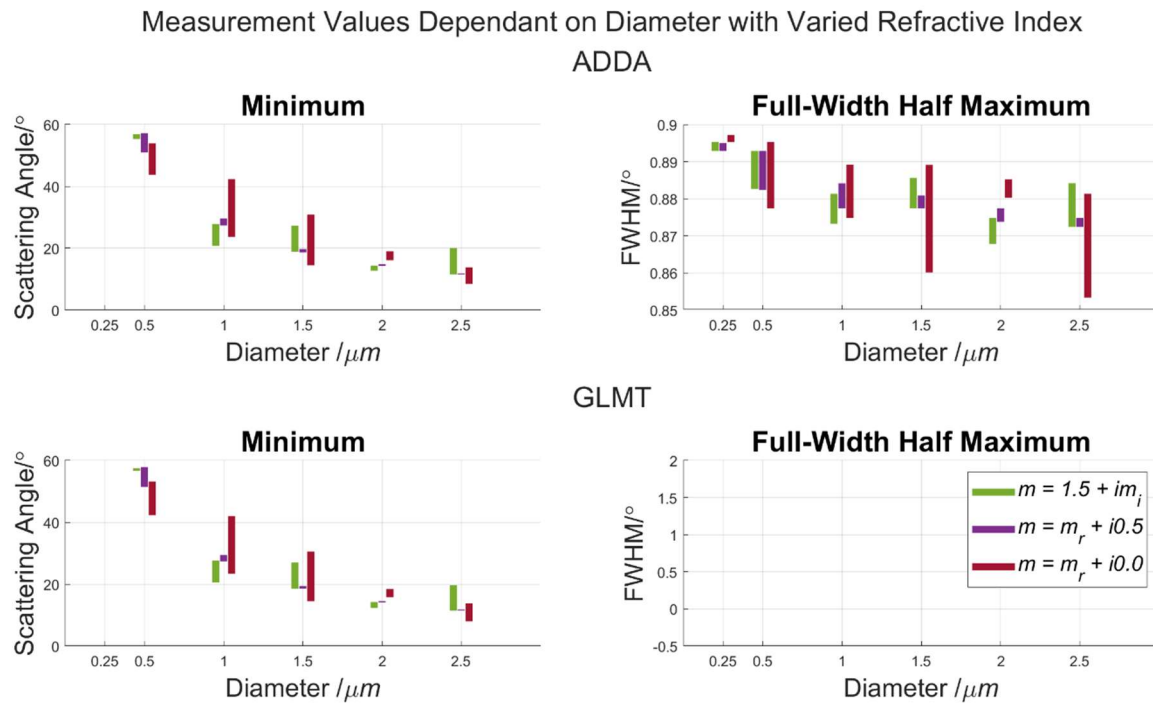


Figure 4.22: Results for the measurements of the angular minimum location (left column) and the FWHM (right column) for both ADDA- (top row) and GLMT- (bottom row) modelled data. The green bars indicate a variation in imaginary refractive index, with a fixed real part of 1.5 ($m = 1.5 + im_i$), the purple bars indicate a variation in real refractive index, with a fixed imaginary part of 0.5 ($m = m_r + i0.5$), and the red bars indicate a variation in real refractive index, with a fixed imaginary part of 0 ($m = m_r + i0.0$).

³⁴ With exception to the $2.5\ \mu\text{m}$ diameter cylinder of refractive indices $1.7+i0$ and $1.95+i0$, which failed to converge when being modelled.

³⁵ Where $m = m_r + im_i$ is the refractive index and the subscripts r and i indicate the real and imaginary parts respectively.

Figure 4.22 (left column) shows the variation of the minimum found when varying the refractive index using ADDA-modelled data (top) and GLMT-Modelled data (bottom). A decrease in variation was found with increasing diameter for $m = m_r + i0.5$, due to the non-linear relationship between the diameter and the minimum, from Figure 4.4 this translates to a maximum variation of around $\pm 2.5\%$. When changing the real part of the refractive index with a low imaginary part ($m = m_r + i0.0$) however, the variation is much larger and translates to around $\pm 10\%$. Similar results were found when varying the imaginary refractive index ($m = 1.5 + im_i$) due to the data where $m = 1.5 + i0.0$ – other imaginary values grouped together. The small variation shown for the change in imaginary refractive index for the $0.5\ \mu\text{m}$ diameter cylinder is due to the minimum not being found for half of the entries, this is also why no data is shown for the $0.25\ \mu\text{m}$ diameters. Figure 4.23 shows examples of the scattering from a $2.5\ \mu\text{m}$ diameter by $10\ \mu\text{m}$ long cylinder at different refractive indices to demonstrate the origin of these large differences.

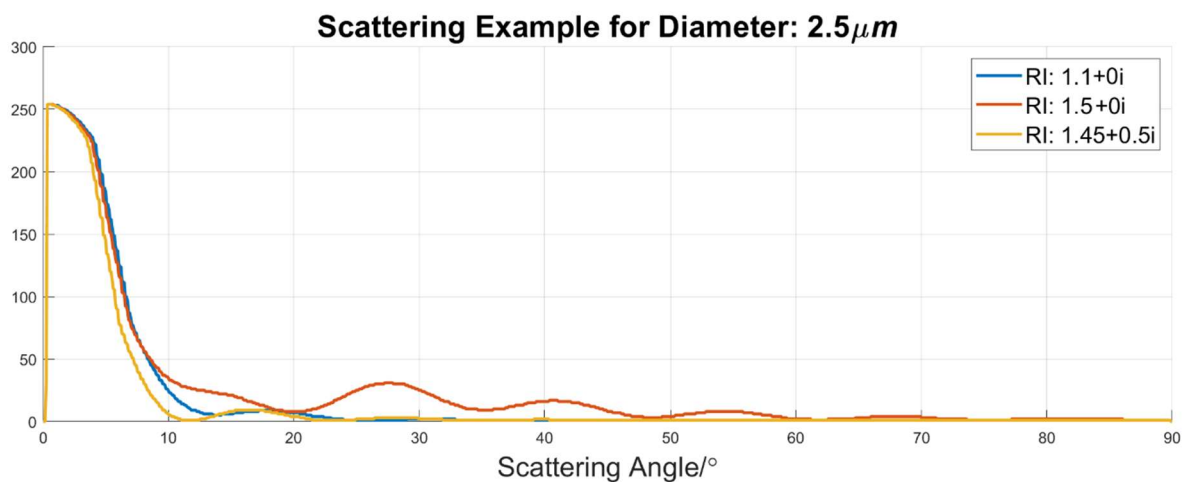


Figure 4.23: ADDA-modelled scattering examples from a $2.5\ \mu\text{m}$ diameter by $10\ \mu\text{m}$ long cylinder with refractive indices of $1.1+i0$, $1.5+i0$, and $1.45+i0.5$, shown in blue, orange, and yellow respectively.

What can be concluded is there is a dependence on refractive index for these potential methods of measurement of the cylinder that the light is scattered from. Fortunately, the corresponding difference caused by the change in refractive index only contributes to a small change in length. For diameter, however, the change in refractive index only contributes to a small change in the minimum when the imaginary part is sufficient. Any variation in refractive index will not have a considerable effect on a diameter measurement if the material has a reasonably high absorption coefficient.

4.2.6 Curvature

As shown in the scattering examples of Chapters 1 and 2, curved fibres produce a bowtie scattering pattern. Some fibres, such as chrysotile asbestos (Langer et al., 1974) are naturally curved and so consideration of fibre curvature is important to their detection and measurement. Unfortunately, several additional problems arise with the inclusion of curved fibres within this project. Out of the two light scattering models chosen, only ADDA can accommodate this shape. However, ADDA contains no pre-defined shape that could approximate a curved fibre and so a 3D model will have to be designed for each modelled fibre. The 3D models also need to be converted into the correct format for ADDA to read and this needs to be applied for every length, diameter, and radius of curvature required to be

investigated. An example is shown in Figure 4.24 of a $0.75\ \mu\text{m}$ diameter curved fibre with a chord length of $10\ \mu\text{m}$ and a radius of curvature $\sim 11.4\ \mu\text{m}$.

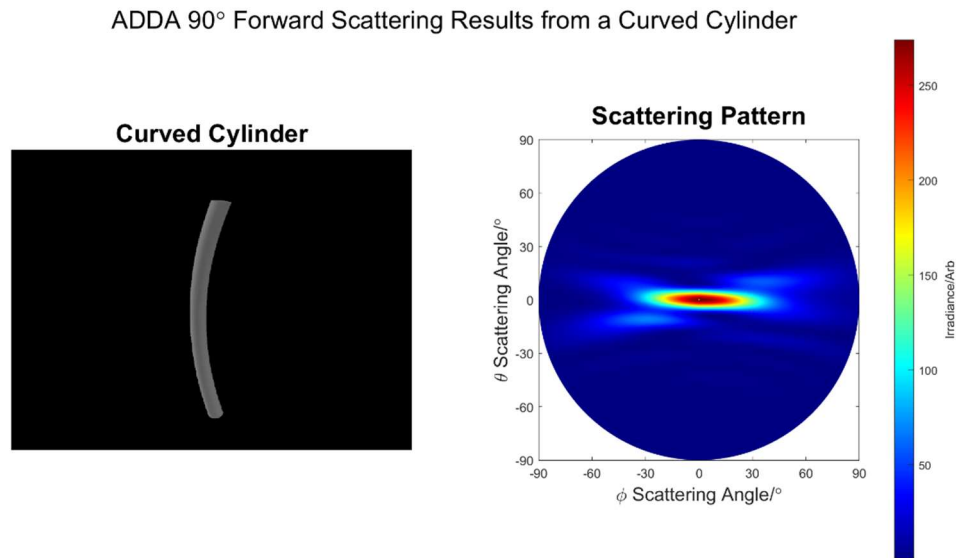


Figure 4.24: A 3D model of a $0.75\ \mu\text{m}$ diameter cylinder of a chord length of $10\ \mu\text{m}$ and a radius of curvature $\sim 11.4\ \mu\text{m}$ (left) and the resulting 90° forward scattering (right). The scattering pattern was modelled in ADDA for refractive index $1.5+0.5i$ at an Euler angle of $(0, 90, 0)$.

A bowtie shaped pattern is found from the resulting scattering pattern and resembles the patterns of curved fibres shown in the examples in Chapter 1. Unfortunately, further investigations into the scattering effect of the curvature of fibres is beyond the scope of this project and so only straight fibres will be used throughout.

4.3 Monte Carlo-Based Experiment

This section will test the reliability of the measurement techniques described in Section 4.2. A set of reference data will be generated for the measurement of the diameter and another set for the length measurement, using both ADDA and GLMT. An additional set of data will be made with pseudo-randomised variables for measuring against the reference data. The input parameters of the ADDA modelled data will be used in the GLMT model to ensure a fair test. This Monte Carlo-based approach allows the analysis of a variety of input variables and how well the measurement algorithm works with those variables. More realistic inputs would be less varied, for example, the measurement of a particular glass fibre would have very little variation in refractive index. A priori information on this example fibre would be known if being monitored for, and thus its refractive index. However, conclusions regarding the limitations of the measurement algorithm may be drawn from the range of the input variables.

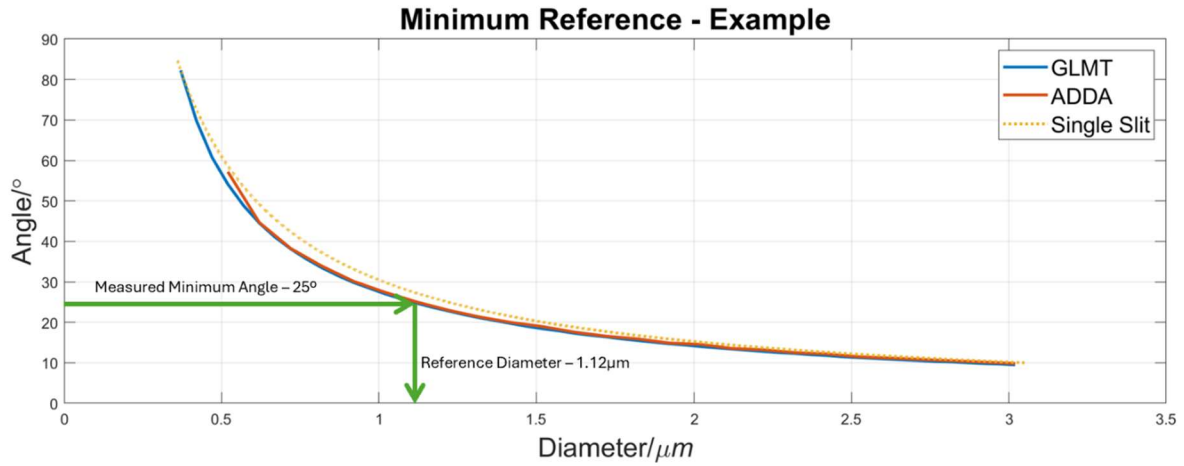


Figure 4.25: Diameter reference data measurement example. Cylinders of a refractive index of $1.5+0.5i$, length $10\text{ }\mu\text{m}$, and an Euler angle of $(0, 90, 0)$ were used to generate the scattering images used to generate the data. A minimum is found at 25° , indicating a diameter of $1.12\text{ }\mu\text{m}$ (green arrows) when using either the GLMT or ADDA reference data. Results from computing the single slit diffraction are included for interest.

Figure 4.25 shows some example reference data for the diameter measurements taken from ADDA-modelled data (orange), GLMT-modelled data (blue), and the relationship between the width of a slit (axis labelled as diameter for simplicity) and the angle in which the first minimum is found (yellow dotted line) according to Equation 2.3, i.e., diffraction theory. The reference data is used as a comparison to the scattering images generated using the randomised variables³⁶. For example, for a diameter measurement, a randomised image is found to have a minimum point at an angle of 25° , the reference data is then used to establish a diameter, as illustrated in Figure 4.25 as the horizontal green arrow. The diameter for the reference data, with a minimum found at 25° , is shown to be $1.12\text{ }\mu\text{m}$ by the vertical green arrow in Figure 4.25, indicating the diameter measurement for the randomised image. The same method is used for the length measurements but using the FWHM values.

4.3.1 Method

4.3.1.1 Parameters

For this investigation the orientation of the cylinder relative to the incident light, has been in a fixed Euler angle of $(0, 90, 0)$. This was done to both test the measurement techniques without having to compensate for the scattering curvature, discussed in Section 4.2.4, and to be able to include the GLMT model for comparison. Additionally, the input parameters for the ADDA model also included the options found during the optimisation process in Chapter 2.

In anticipation of applying these measuring techniques to real life data, measured from forward light-scattering devices such as PPD2, limitations have been introduced to emulate the measured data. The scattering images captured by PPD2 have an upper angular limit of 26° about the forward scattering direction, and lower limit of around 6° due to the beam-stop. Measurements taken from the modelled data have been limited to these angles. Additionally, the modelled data were converted into a more representative state that could be applied to a physical system to create more realistic results, shown in Section 4.3.1.4.

³⁶ Referred to throughout as just “Randomised images”

4.3.1.2 Reference Data

The reference data for the diameter measurements were generated in ADDA and GLMT from cylinders of length 10 μm and a refractive index of $1.8+0.8i$. The choice of refractive index is due to the optimisation process discussed in Section 4.5.2. A series of different diameters were used between 0.02 μm and 3.02 μm , as described previously, to conform to the WHO regulations on respirable fibres. Another set of reference data was generated for the length measurements from cylinders of a fixed diameter of 0.5 μm and a refractive index of $1.8+0.8i$. The lengths ranged from 5 μm to 50 μm to conform with the minimum length of the WHO regulations on respirable fibres. No upper limit is given in the WHO regulations for the lengths of respirable fibres but after the investigation in Section 4.2.2, not much difference in the FWHM measurements were found after $\sim 20 \mu\text{m}$ and almost none between 50 μm and 100 μm – see Figure 4.7.

4.3.1.3 Randomised Data

A set of pseudo-randomised data was generated for testing using both ADDA and GLMT. Again, the orientation was a fixed Euler angle of (0, 90, 0). However, the length, diameter, and refractive index were randomly chosen using a pseudo-random number. Both the diameter and the length were randomly chosen between the limits described previously. A few lengths under 5 μm were included as a way of determining how the measurement algorithm would handle something beyond the limits of the reference data. The real and imaginary parts of the refractive index were randomly chosen between limits of 1 – 3 and 0 – 1 respectively. These limits were chosen to be as sensibly representative of the range of refractive indices found in common materials as possible.

4.3.1.4 Features

As shown in Section 4.2.2, the length of the cylinder is related to the FWHM measurement of the bright band of the scattering pattern produced. The FWHM found for the smallest length is no larger than 6° and so will not be affected by the limitations of the instrument by having any of the scattering data truncated. The first angular minimum location, however, is located beyond 26° for diameters of around 1.2 μm and so a minimum for smaller cylinders will not be found by the instrument. This difficulty in finding the minimum for smaller diameters is reinforced by the examples made in 4.2.3.1, where the algorithm struggled to locate shallower minima. To compensate, an alternative measurement approach is employed. When observing the scattering patterns of a smaller diameter cylinder a feature that is within the angular limits and that makes a noticeable change is the shape of the central peak. A gradient of a line of best fit between 6.75° and 9.5° of the central vertical component of the scattering image has been taken³⁷, shown in Figure 4.26, and measured over a range of diameters.

³⁷ Referred to throughout as the “gradient” measurement with units of irradiance/scattering angle that will be represented using ΔI .

Diameter Measurement Reference & Example

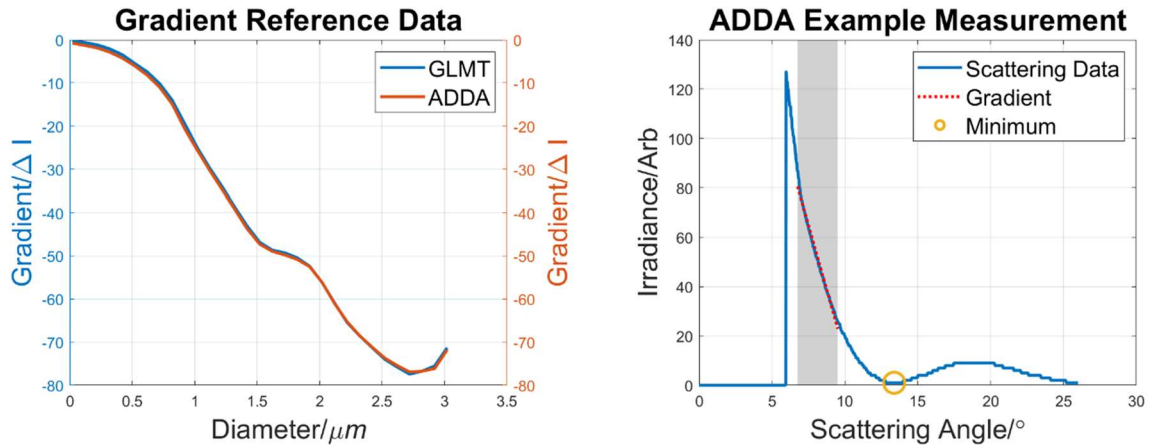


Figure 4.26: The gradient of a line of best fit between the scattering angles of 6.75° and 9.5° of the central vertical component of the 26° forward scattering of a $10\ \mu\text{m}$ long cylinder modelled in both ADDA (orange) and GLMT (blue) for different diameters (left). Right shows an example of the scattering and the way in which the gradient is measured along with a yellow circle indicating the minimum.

The example shown in Figure 4.26 (right) is the central vertical component of an ADDA-modelled light scattering pattern (blue line). The angles between 6.75° and 9.5° is the grey shaded area and the dotted red line shows the line of best fit of the ADDA data within it. Below the 6° mark the irradiance is zero due to the beam-stop. For this example, data from the reference image is shown for an input diameter of $2.12\ \mu\text{m}$ giving a gradient of -20.816 . However, as the minimum can be found, the gradient measurement is not needed.

The gradient measurement found is non-monotonic beyond about $2.7\ \mu\text{m}$ diameter, however, the point at which the measurement becomes non-monotonic overlaps with the lower limit of the minimum measurements at a diameter of around $1.6\ \mu\text{m}$ – see Figure 4.28. The reason for the non-monotonic shape of the data in Figure 4.26 (left) is due to the minimum point that moves closer to the 0° scattering angle, shown in the example in Figure 4.26 (right). When the minimum is sufficiently close to the gradient measurement area it interferes with the line of best fit and so won't be used as reference data.

Additionally, for considerations of the optical design of potential future instrumentation, the way in which the scattering data is measured has been fashioned to emulate realistic systems. One method is to use the mean value of the image for both the vertical and horizontal directions, creating two sets of array data. This would be analogous to splitting the scattered light and focusing both results, with orthogonally oriented cylindrical lenses, onto a detector and is referred to as the “total” method. Another method is to take the mean of different rectangular sections of the scattering data, similar to using a linear array set-up (e.g. Mahrt et al., 2019; Ruske et al., 2017; Stopford et al., 2013; Wieder, 2018) and is referred to as the “section” method. A graphical representation of these methods is shown in Figure 4.27.

Light Scattering Measurement Set-Up
for a $1.52\mu\text{m}$ Diameter $\times$ $10\mu\text{m}$ Long Cylinder

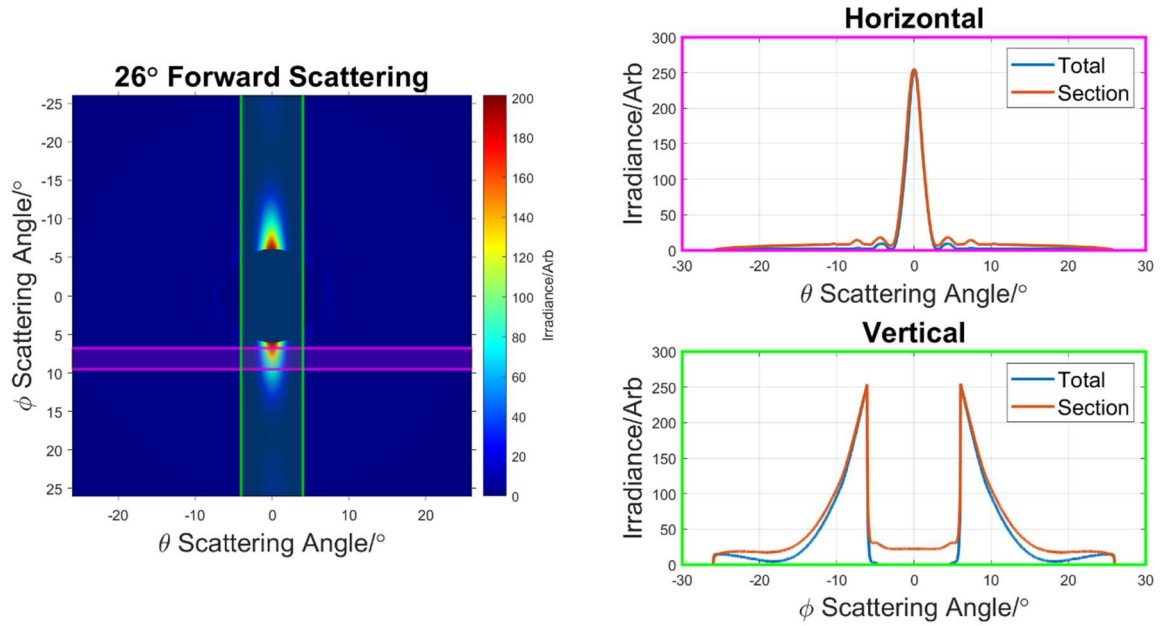


Figure 4.27: 26° forward scattering of a $1.52\mu\text{m}$ diameter by $\sim 10\mu\text{m}$ long cylinder modelled in ADDA (left). The green vertical section and the magenta horizontal section represents two linear arrays, the averages of these sections are shown on the top right and bottom right respectively.

Finally, using the described total and section methods, two sets of reference data have been created for both models used. Figure 4.28 shows the reference data modelled from both ADDA (top) and GLMT (bottom), from left to right the plots show the first angular minimum location depending on diameter, the gradient of the line of best fit of the scattering data between the angles of 6.75° and 9.5° depending on diameter, and the FWHM measurement depending on the length. The choice of the angular limits given are due to the optimisation process discussed in Section 4.5.1. The blue results represent the total measurement technique, i.e. measurements taken from the mean of the vertical or horizontal component of the image. The orange results represent the section measurement technique, i.e. measurements taken from the mean values of the green and magenta sections highlighted in Figure 4.27.

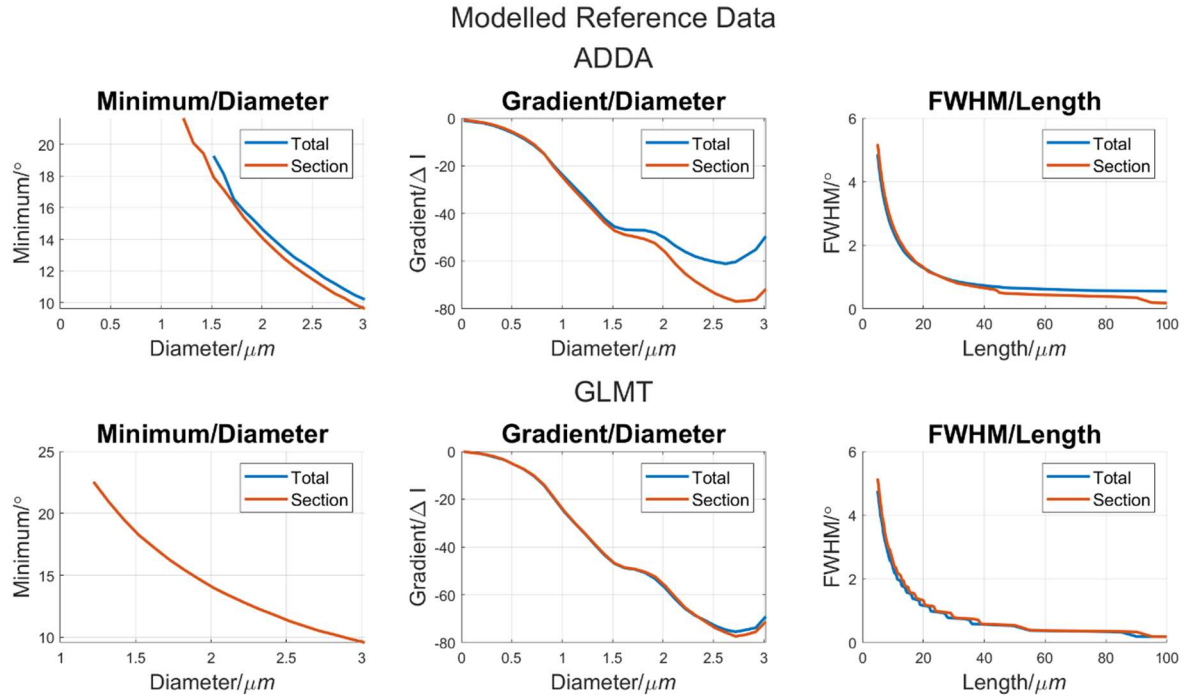


Figure 4.28: Reference data created using ADDA model (top) and GLMT model (bottom) for the minimum depending on diameter (left), gradient of the scattering depending on diameter (centre), and the FWHM depending on the length (right).

4.3.2 Results

4.3.2.1 Diameter

Using the two sets of reference data a diameter can be found from the scattered light of the randomised input cylinder using minimum and the gradient measurements, shown in Figure 4.28 (left and centre respectively). If no minimum is found, the gradient method is used. Results for the ADDA modelled data is shown in Figure 4.29 with the section method on the left and total method on the right.

ADDA Diameter Measurement Comparison Results

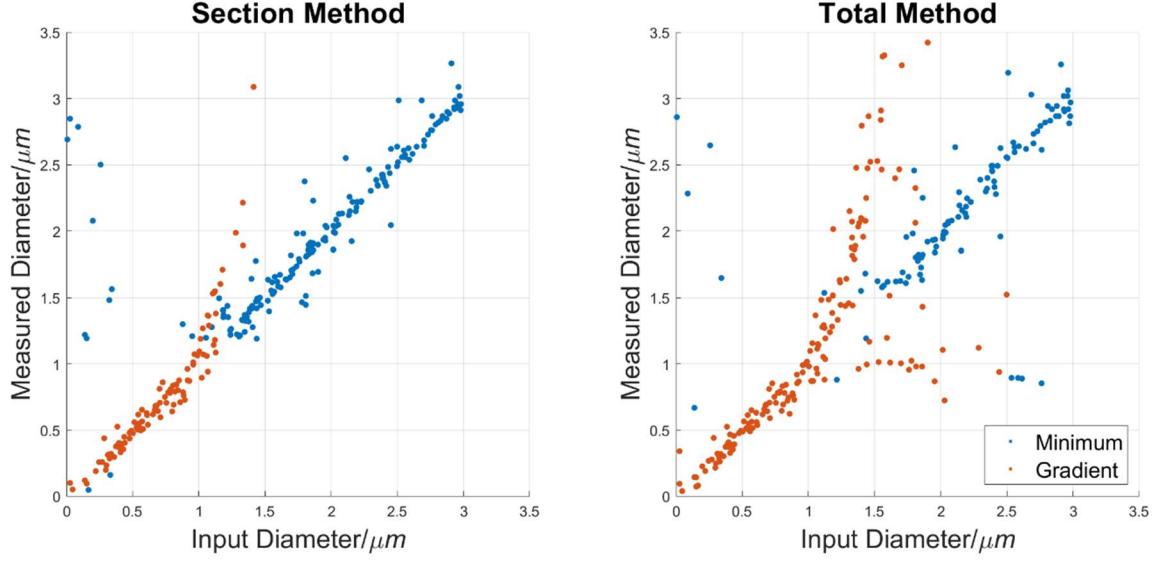


Figure 4.29: Diameter measurement results from ADDA modelled data using the section method (left) and the total method (right). The blue represents the measurements using the minimum and the orange represents the measurements using the gradient. The measurements (Measured Diameter) are plotted against the input diameter.

Generally, the results for the section method shown in Figure 4.29 (left) follow a 1:1 trend, indicating a good system of measurement. The large outliers found for the gradient measurements in Figure 4.29, that occur after $\sim 1 \mu\text{m}$ are due to the reference data; the slight “saddle” found at $\sim 1.5 \mu\text{m}$ in Figure 4.28 (centre top and bottom) increases the sensitivity of the measurements, resulting in gradient measurements (orange) for diameters larger than $1 \mu\text{m}$ to become erratic. The large outliers with an input diameter of $\sim 2.5 \mu\text{m}$, found for the minimum measurements (blue) in Figure 4.29 (right) are due to some minimum points being mislocated by the algorithm, finding minimum points from noise, resulting in obvious mismeasurements. The large outliers for an input diameter of $\sim 0.25 \mu\text{m}$ are due to these points being found beyond the limits of the reference data, causing wild mis-interpolations. The smaller outliers for the minimum measurements are due to refractive index, as explained later in this section.

The more obvious outliers, showing to be over-sized from the minimum measurements, are a result of minimum points being mis-located due to noise. However, both the section and total methods show a loss in accuracy where the gradient measurements and the minimum measurements meet at around $1.2 \mu\text{m}$, the total method more so than the section one. R-squared values were found through a $y = x$ function to indicate how well the total measured diameters compared with the input diameters, this was achieved using Equation 4.1. Values of ~ 0.76 and ~ 0.62 were found for the section and total methods respectively.

$$R2 = 1 - \frac{\sum_i (D_i^{in} - D_i^{out})^2}{\sum_i (D_i^{in} - \bar{D}^{in})^2}$$

Equation 4.1

where D is the diameter, the superscripts in and out are associated with the input and measured (output) diameters respectively, and $R2$ is the resulting R-squared value.

The same process has been repeated using the GLMT, results shown in Figure 4.30, that has used the ADDA input parameters to generate the randomised and reference scattering images to be analysed.

GLMT Diameter Measurement Comparison Results

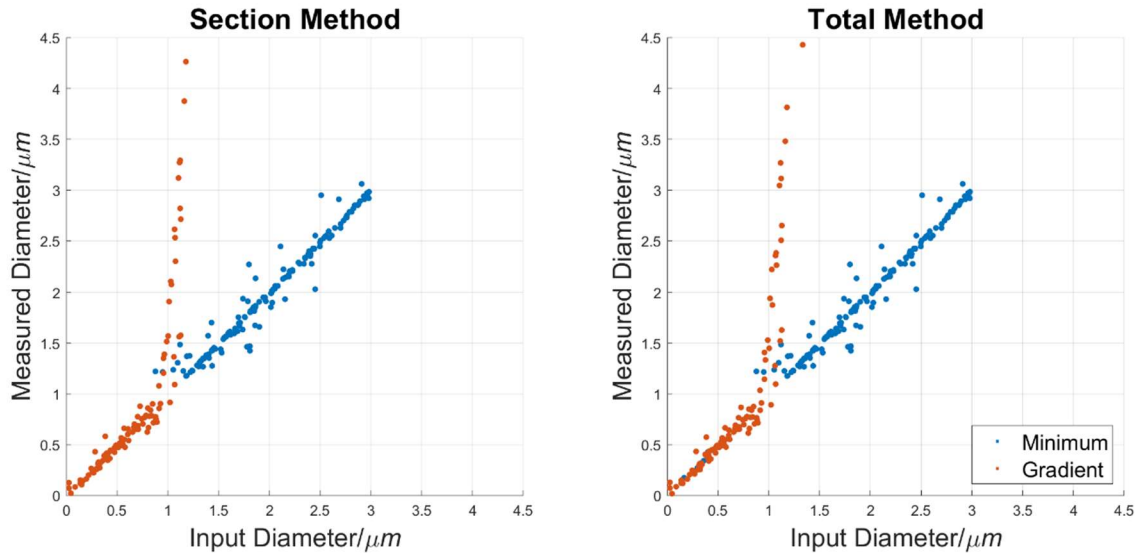


Figure 4.30: Diameter measurement results from GLMT modelled data using the section method (left) and the total method (right). The blue represents the measurements using the first angular minimum locations and the orange represents the measurements using the gradient. The measurements (Measured Diameter) are plotted against the input diameter.

The same 1:1 trend is noticed in the results shown in Figure 4.30 such as what was found in the ADDA results of Figure 4.29. Overall, the GLMT data show better results for the diameter measurements than the ADDA data, aside from the gradient measurement oversizing that occurs at around a diameter of 1 μm , suspectedly due to the mis-interpolation of the data. The comparison to a $y = x$ function to the GLMT results showed R-squared values of ~ 0.77 for both the section and total methods.

The outliers along the 1:1 trend, not including the over-sizing from the gradient measurement method, can be attributed to the imaginary refractive index. Figure 4.31 shows the same ADDA diameter measurement results but with the gradient and minimum methods separated and the points colour-coded to show the imaginary part of the refractive index.

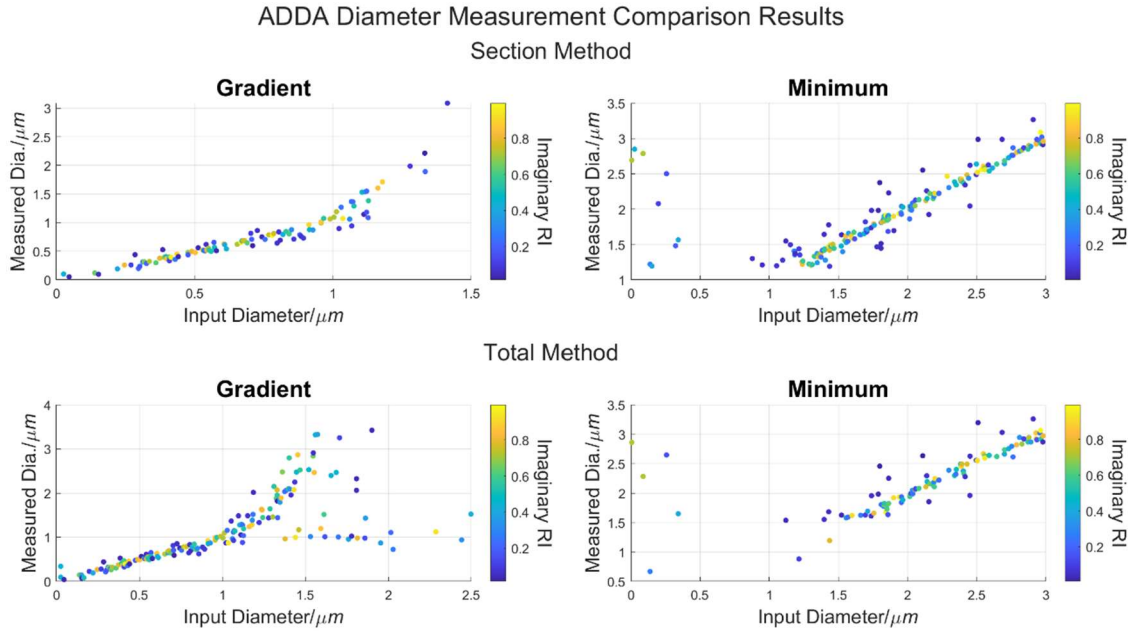


Figure 4.31: Diameter measurement results from ADDA modelled data using the section method (top) and the total method (bottom). The plots on the left-hand side show the diameter results using the gradient method and the plots on the right-hand side show the results of the minimum method. The scatter points are colour-coded to the imaginary part of the refractive index, shown as a colour bar on the right-hand side of the plots.

The imaginary refractive index colour-coded results for the GLMT model are shown in Figure 4.32.

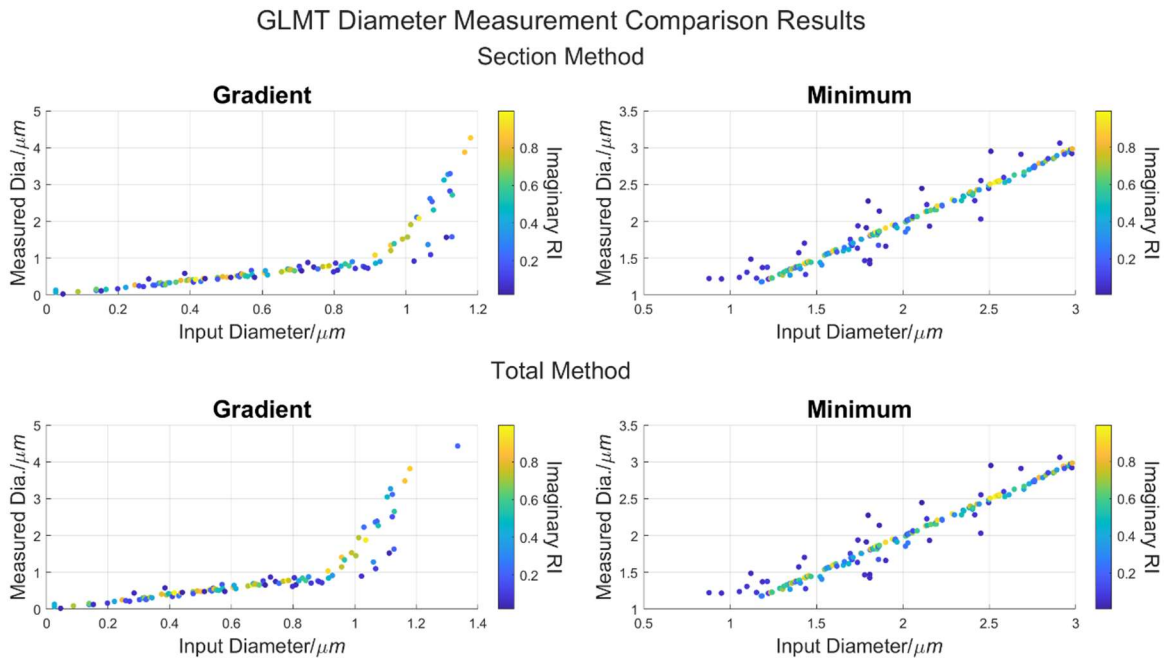


Figure 4.32: Diameter measurement results from GLMT modelled data using the section method (left) and the total method (right). The plots on the left-hand side show the diameter results using the gradient method and the plots on the right-hand side show the results of the minimum method. The scatter points are colour-coded to the imaginary part of the refractive index, shown as a colour bar on the right-hand side of the plots.

The real part of the refractive index was also used to produce the plots like those shown in Figure 4.31 and Figure 4.32, found in Appendix 7.3, but showed no pattern like the imaginary part did, wherein the majority of the outliers had the lowest imaginary refractive index.

4.3.2.2 Length

The FWHM length-measurement results are shown in Figure 4.33 which shows the cylinder length of the randomised data, measured using the reference data, plotted against the input length for the ADDA modelled data. Again, the left plot of Figure 4.33 shows the results of the section method and the right shows the results of the total method.

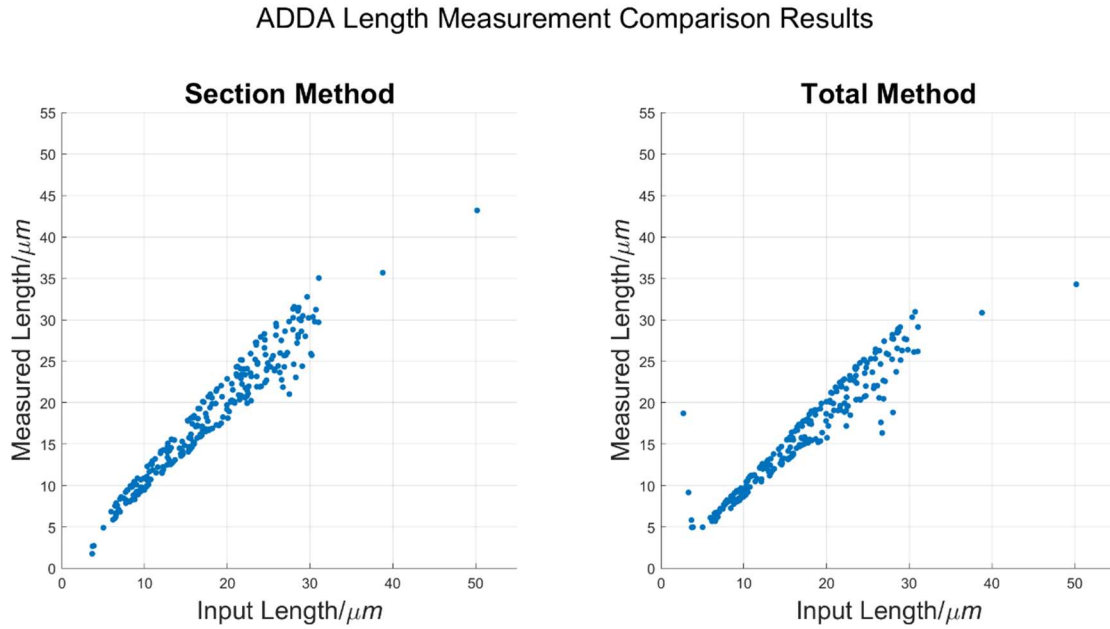


Figure 4.33: Length measurement results from ADDA modelled data using the section method (left) and the total method (right).

Another 1:1 trend is noticed for both, indicating a good method of measurement. The $y = x$ function fitted to these data found R-squared values of ~ 0.93 and ~ 0.86 for the section and total methods respectively. The outliers seen in the total method in Figure 4.33 (right) for the smaller lengths are from those of input lengths of less than $5 \mu\text{m}$ and beyond the lower limits of the reference data. The removal of these data points does increase the R-squared value but not by much. Additionally, unlike the diameter measurement results, no negative measurements were found.

Finally, the length measurements using the GLMT modelled data are shown in Figure 4.34. The $y = x$ function that was fitted to the GLMT results found R-squared values of 0.64 and 0.98 for the section and total methods respectively. Again, the outliers found using the section method in Figure 4.34 (left) are from lengths less than $5 \mu\text{m}$.

GLMT Length Measurement Comparison Results

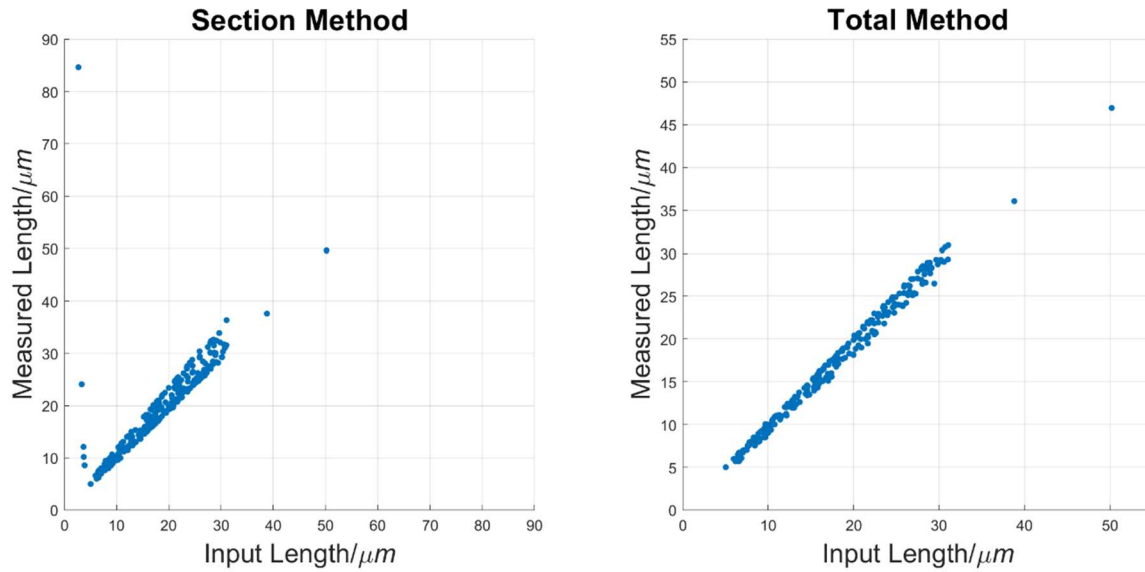


Figure 4.34: Length measurement results from GLMT modelled data using the section method (left) and the total method (right).

The refractive index seemed to show no influence on the results of the length measurements, the plots containing the indicators for both real and imaginary refractive index for both models are found in Appendix 7.3.

4.3.2.3 Investigating Outliers

Further investigations into the source of the larger outliers found for the results in Section 4.3.2.1 and Section 4.3.2.2 lead to an explanation. Unfortunately, due to time restrictions, a solution was not found.

For the diameter, measurements of the gradient found in the ADDA-modelled data were plotted against the measured diameter (blue dots), shown in Figure 4.35 (top), and compared with the gradient reference data (orange line). Any gradient measurements smaller than -20 diverge from the reference data, a similar trend is seen with the GLMT-modelled data (found in Appendix 7.3), but this diverging starts at around -15. The gradient values of -20 & -15 correspond to a diameter measurement of $\sim 1 \mu\text{m}$ and explain the poor results found for the gradient measurements beyond this limit – see Figure 4.29 and Figure 4.30. Similarly, Figure 4.35 (bottom), shows the same data, but for the minimum measurements. Below a diameter of $1.5 \mu\text{m}$ for both the total and section methods, the algorithm shows poor interpolation of the minimum measurements and explains the poorer results of the ADDA-modelled data, compared to the GLMT-modelled data at this lower limit: the GLMT-modelled data (see Appendix 7.3) did not exhibit the same mis-interpolation of data.

Measured and Reference Diameter Comparisons for ADDA-Modelled Scattering Images

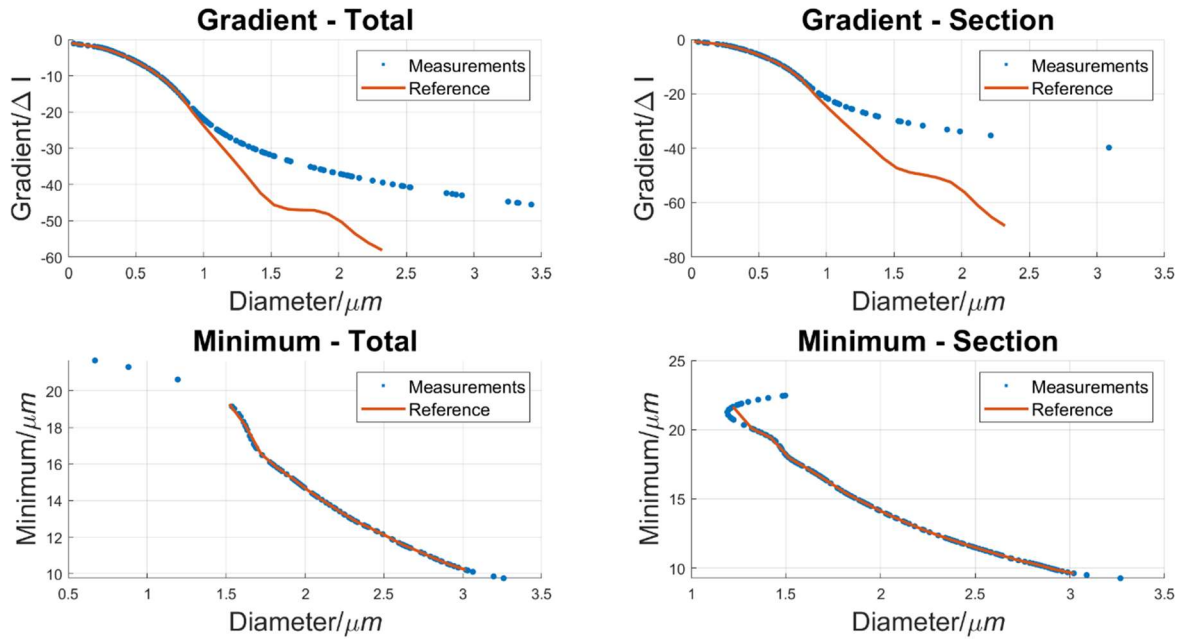


Figure 4.35: Comparisons of the measured and reference diameters from the ADDA-modelled data. Top row shows the reference data (orange) for the gradient measurements for both the total and section methods (left and right respectively). Overlaid (blue dots) are the gradient measurements plotted against the measured diameter. The bottom row shows the same results but for the minimum measurements.

Similar results were found for the length measurements, as shown in Figure 4.36, from the ADDA-modelled data. Beyond the limits of the reference data, the interpolation of the FWHM measurements have caused some inaccurate length measurements. The results for the GLMT-modelled data (see Appendix 7.3), however, do not exceed the limits of the reference data.

Measured and Reference Length Comparisons for ADDA-Modelled Scattering Images

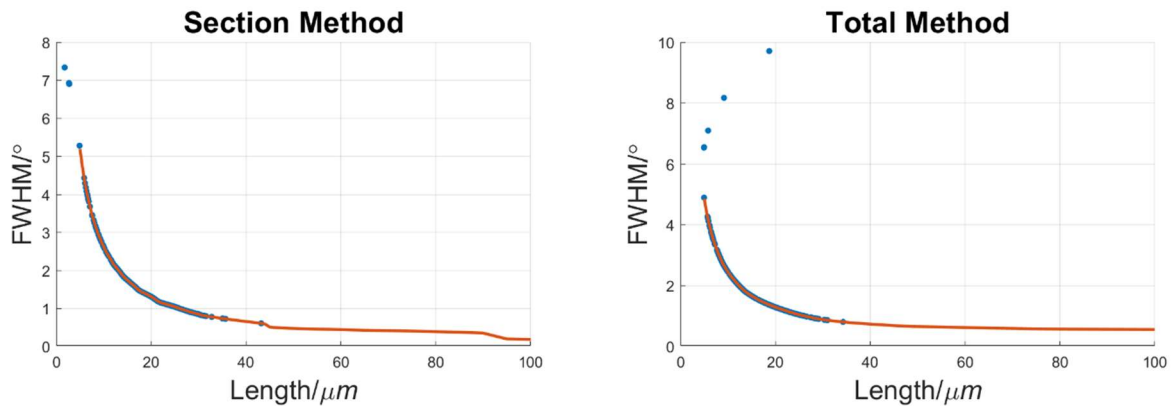


Figure 4.36: Comparisons of the measured and reference lengths from the ADDA-modelled data. The plots show the reference data (orange) for the FWHM measurements for both the total and section methods (left and right respectively). Overlaid (blue dots) are the FWHM measurements plotted against the measured Length.

Fortunately, the problems found with the length measurements were much less severe than those found for the diameter measurements.

4.4 Discussion

Results shown in the previous section all demonstrate that the measurement methods of Section 4.3.1 show a certain level of suitability in measuring the size of a cylinder, using the 6° to 26° forward scattered light. The separation of the large and small diameters was necessary to compensate for the limitations of the scattering angle captured by PPD2, but due to the reduction in the prominence of the minima³⁸ with decreasing diameter, this would have been necessary regardless. The results regarding the transitional area between the two methods, shown in Section 4.3.2.1 to be ~1 µm for the GLMT data and ~1.25 µm for the ADDA data, found to diverge from the trend – further work would be needed to optimise this and minimise the outliers. The refractive index only seemed to affect the diameter measurements and only when the absorption coefficient is very low – length measurements were seemingly unaffected.

The diameter measurement results using the gradient measurement method all showed a good 1:1 match for the input data at small diameter values which eventually became worse for larger sizes when using the ADDA-modelled data. The total method produces similar results to the section method for smaller diameters but began to diverge at a diameter of ~1 µm a lot more so than the section method. These large outliers were found to be the result of the mis-interpolation of the reference data. The smaller outliers seem to be the result of the shape of the reference data; for very small diameters, i.e., gradient values close to zero, the curve of the reference data starts to flatten, increasing the sensitivity.

The diameter measurement results using the minimum measurements all showed similar results regardless of the light scattering model or measurement method. The outliers found were the result of a very low imaginary refractive index but were still all within ~20 % of the input diameter. Overall, both the GLMT-modelled data and the ADDA-modelled data all showed comparable results for the diameter measurements, however, some diameters close to the lower 1.5 µm limit were mis-interpolated when using the ADDA-modelled data.

The main problem with the diameter measurements is the uncertainty between 1 µm and 1.5 µm in diameter. This range of diameters are subject to being mis-measured using the current methods of measurement. This could be ameliorated with the refining of the interpolation algorithm used to cross-reference between the measured gradient or minimum to the diameter. Unfortunately, due to time restrictions, no further investigation into this can be done for this project.

The length measurement results using both the section and total methods, shown in Section 4.3.2.2 show a conical shape about the general 1:1 trend. The conical shapes were the result of the input diameter; when colour-coding the length results using the input diameters (see Appendix 7.3) a clear trend of oversizing is seen with decreasing diameters. This may be due to the reduction in irradiance of the section used for these measurements from the minimum coinciding with the angular limits of the section. Additionally, the larger outliers can be explained from the reference data, additional data may help to resolve this problem. Unfortunately, as the GLMT modelled data is made finite by a diffraction approximation, results using this model may not be representative of real scattering data from fibres. This is reflected in the diameter-coloured length measurement results (see Appendix 7.3) as the placement is random, unlike the results of the ADDA data.

³⁸ See Section 4.2.3.1.

4.5 Optimisation

4.5.1 Gradient Measurements

To determine the diameter values for smaller cylinders, the gradient measurements of the scattering were required, and to find the optimum angular limits³⁹ for this a series of tests were made. A lower limit of 6° was already established from the scattering limitations caused by the beam-stop. The upper limit was set to 14.5° - this does overlap with the minimum measurements of cylinders with a ~2 µm diameter and was expected to show poorer results, however, it was included to demonstrate its unsuitability. The limits were varied by 0.75° between these two limits to produce 78 sets of data, that includes the two reference data sets and the randomised set, for both ADDA and GLMT modelled scattering patterns. Each set was used to produce results as shown in Section 4.3.2 and an R-squared value of the diameter gradient measurements compared to a function of $y = x$ was found. The results for the ADDA model are shown in Figure 4.37 as a heat map where the y-axis indicates the smaller angle limit in where the gradient measurement begins, the x-axis indicates the larger angular limit, where the gradient measurement ends, and each entry shows the R-squared value found.

Reference Data Gradient Location Dependence on Diameter Results for the ADDA Model

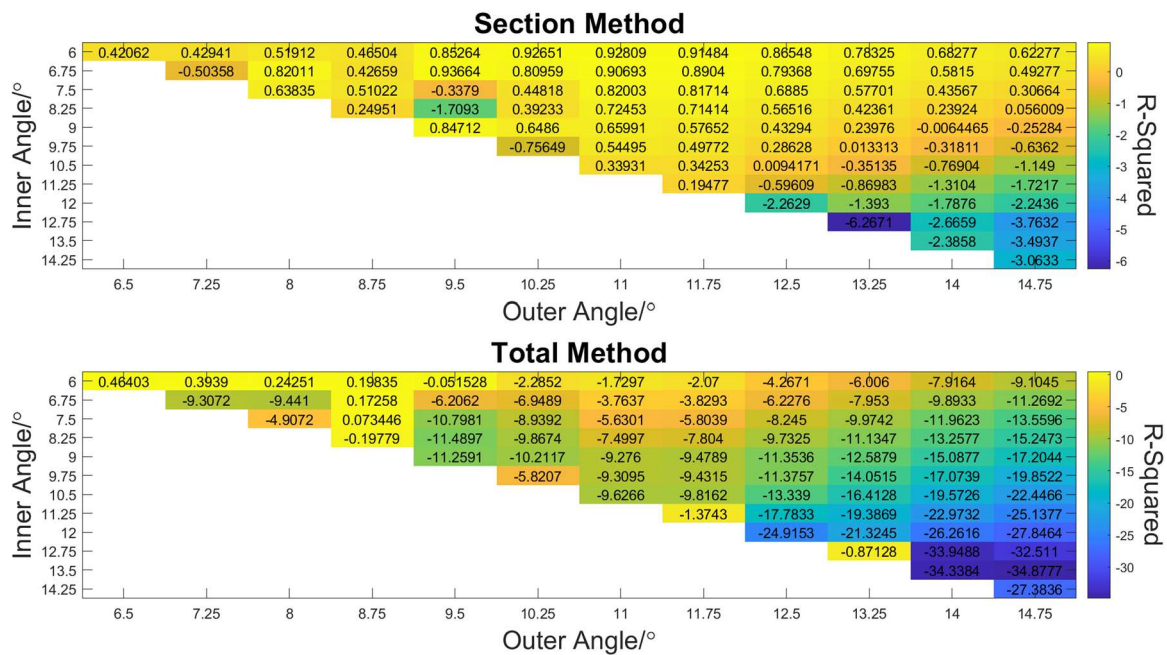


Figure 4.37: R-squared values for the gradient diameter measurement results compared to a function of $y = x$ for data modelled in ADDA. The top shows the results using the section method, the bottom shows the results using the total method. The y-axis indicates the smaller angular limit, closer to the forward scattering direction, the x-axis indicates the larger angular limit.

The R-squared results for the gradient optimisation for the GLMT model are shown in Figure 4.38.

³⁹X-axis angular locations determining the start and end points for gradient line to be measured.

Reference Data Gradient Location Dependence on Diameter Results for the GLMT Model

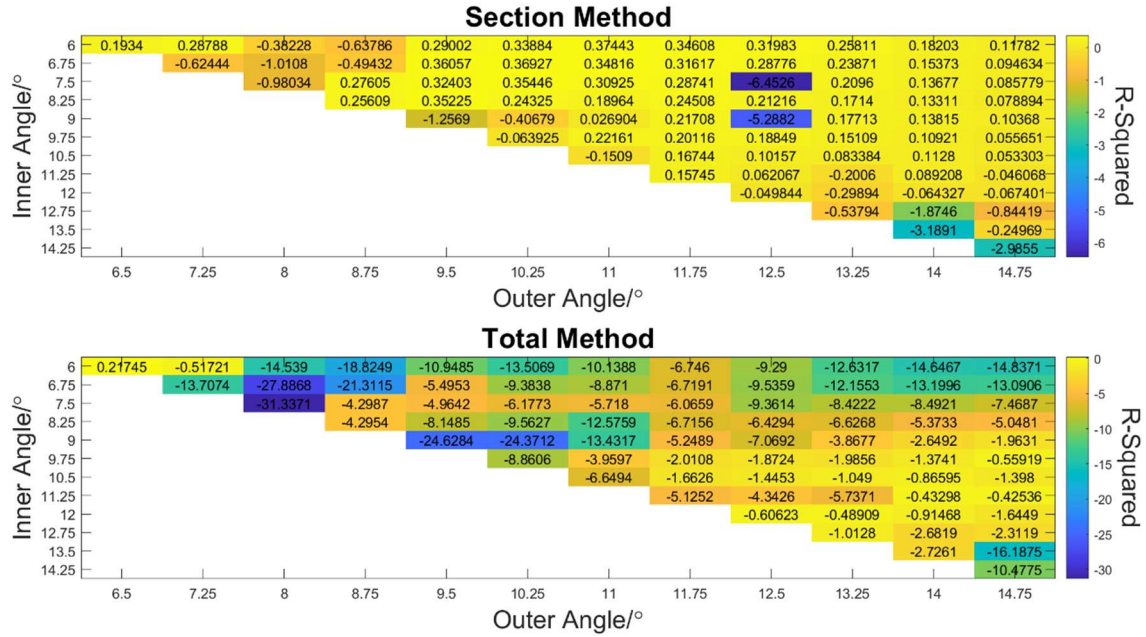


Figure 4.38: R-squared values for the gradient diameter measurement results compared to a function of $y = x$ for data modelled in GLMT. The top shows the results using the section method, the bottom shows the results using the total method. The y-axis indicates the smaller angular limit, closer to the forward scattering direction, the x-axis indicates the larger angular limit.

The results shown in Figure 4.37 and Figure 4.38 allow the determination of the optimal angular limits of the gradient measurement with the R-squared value closest to one. The section method for the ADDA model found this limit to be $6.75^\circ - 9.5^\circ$ with a R-squared value of ~ 0.94 , the best R-squared value across both models and measurement methods. The total method using ADDA showed the optimal limits to be $6^\circ - 6.5^\circ$ with an R-squared value of ~ 0.46 . The section method from the GLMT modelled data showed the optimum limits to be $6^\circ - 11^\circ$ with an R-squared value of ~ 0.37 . The total method for the GLMT modelled data showed the optimum limits to be $6^\circ - 6.5^\circ$, corresponding with the ADDA results but with a lower R-squared value of ~ 0.2 .

Due to the R-squared value of ~ 0.94 , found using the section method from the ADDA modelled data, that was more than two-times greater than the other optimised results, the angular limits for the gradient measurement were set to $6.75^\circ - 9.5^\circ$. This obviously affected the outcome of the results of Section 4.3.2 when comparing the different models and measurement techniques as the same angular limits used for the section method of the ADDA data. These limits used were sub-optimal for the other methods and the GLMT model, resulting in less than satisfactory measurement results. However, as the R-squared value was much better in comparison, the corresponding limits were chosen.

4.5.2 Refractive Index

Prior to the results shown in Section 4.3.2, a series of GLMT reference data sets were used to determine the most suitable refractive index to use. A set of 30 different refractive indices were used to create 60 sets of reference data: 30 for both length and diameter alterations. GLMT was used since more than 4000 images needed to be generated and ADDA would have taken too long to complete these modelled scattering images in a reasonable timeframe, as explored in Chapters 2 and 3. Each of the reference data sets were then used to measure the randomised

data and the R-squared value of the results for both the section and total measurement methods for length and diameter measurements were recorded. Results for both the length and diameter measurements for both measurement methods are shown in Figure 4.39.

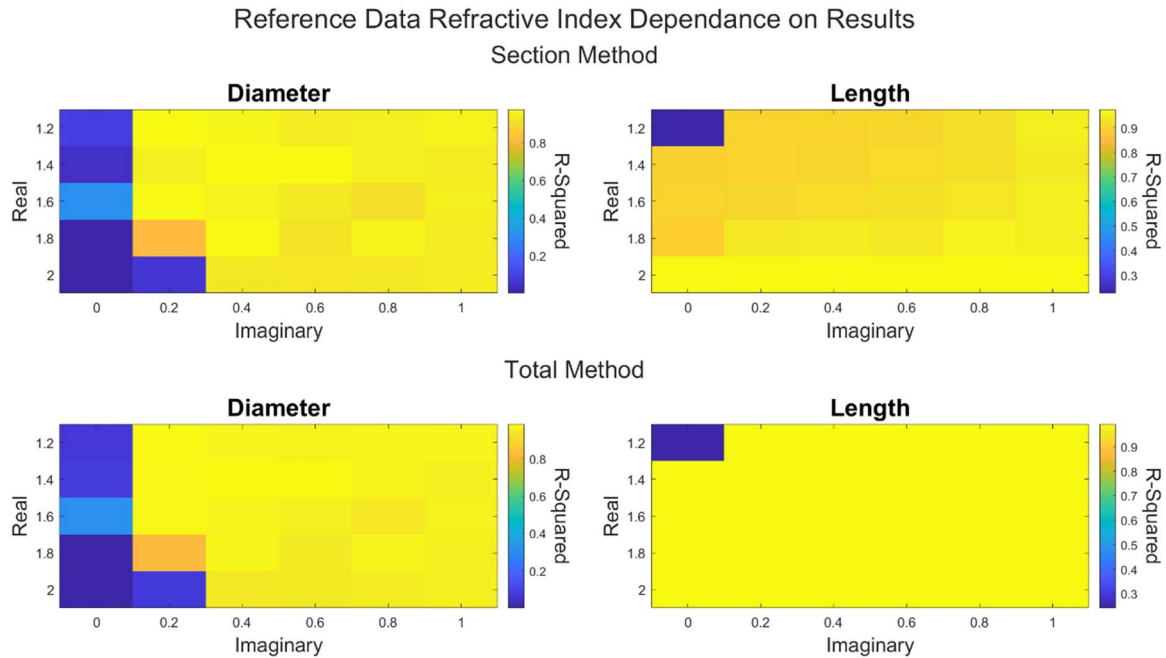


Figure 4.39: Heatmaps of R-squared values found from the results of the length measurements (right) and the diameter measurements (left) for both the section (top) and total (bottom) measurement methods using different refractive indices.

Worse R-squared values were found for the diameter measurements at low refractive indices and, unsurprisingly, there was little variation in the length measurements due to the way in which the length approximation is made – see Section 2.3.2.3. Grouping these results together, i.e., the different measurement methods and the different size measurements for each refractive index value, and taking the mean value is shown in Figure 4.40 with the R-squared values included in the heatmap. This was done to simplify the data in Figure 4.39 and help make a selection of the most appropriate refractive index.



Figure 4.40: Heatmap of the mean R-squared value found for both diameter and length measurement methods using reference data of different refractive indices.

As there were a few optimum choices, five different R-squared values of 0.97, the refractive index chosen to be used as reference data was $1.8+0.8i$.

4.6 Conclusion

From the results of Section 4.3.2, there shows a strong correlation between the measured lengths and diameters from the forward scattering patterns and the input variables used to model those patterns. The ADDA modelled data showed the best diameter results when using the section method but showed better length measurement results from the total method. Conversely, the diameter measurements from the GLMT modelled data showed the inverse. The use of these measurement techniques on real, measured data may require a mixture of both ADDA and GLMT reference data for the most representative measurement results. Overall, ADDA outperformed GLMT, for the sake of simplicity and for future-proofing purposes for both orientation and curvature, only ADDA-Modelled data will be used in Chapter 5. Additionally, due to the diameter problems between $1\text{ }\mu\text{m}$ and $1.5\text{ }\mu\text{m}$, as discussed in Section 4.3.2.3, it is to be expected that there may be problems with this diameter range when regarding the results of Chapter 5. Fortunately, this information would still allow the determination into whether or not the fibre falls within the respirable range.

Currently, these measurement methods do not account for the orientation of the cylinder, this is expected to cause problems, especially using the total method of measurement. However, Section 4.2.4 demonstrates that the curvature of the scattering image, caused by the β -angle orientation, can be measured and is only significant beyond an angular limit. Further investigation is required to compensate for this or find an error. For the purpose of demonstrating that this measurement method works within a sensible timeframe, it was necessary to only use Euler angles of $(0, 90, 0)$. When testing this method with data captured by PPD2 in Chapter 5, scattering images with too much of a curved pattern will be manually

removed. Additionally, as discussed in Chapter 1, the flow alignment of respirable fibres can be easily achieved.

The overall results of this chapter show a promising method for the measurement of cylinder length and diameter from the 26° forward scattering pattern. Chapter 5 uses these techniques on scattering images captured by PPD2 from a selection of different respirable fibre samples. The aerosolised fibres, captured onto a filter, were analysed by optical microscopy after the scattering images were captured. By comparing the size distributions of the light scattering measurements and the micrograph measurements, the techniques explored within this chapter can be tested for their validity.

5 Experimental Verification

*“Some Kinds of failures are better than other kinds.”
-George Orwell, Nineteen Eighty-Four, 1949*

5.1 Introduction

5.1.1 Motivation

The following experiment was conducted to verify the image analysis techniques described in Chapter 4. A selection of respirable fibre samples were aerosolised separately into a chamber attached to the PPD2 instrument. The scattering images of the fibre samples were captured and the fibres themselves collected onto separate filters. Size distributions measured from the scattered light were compared with the size distributions of the filter-collected fibres through optical microscopy. The comparison of the size distributions were used to ascertain the reliability of the measurement techniques described in Chapter 4.

5.1.2 Similar Work

There are few examples found in literature that conduct similar experiments to that described in Section 5.1.1; where light scattered from single aerosol is compared with both modelled data and micrographical analysis. Hirst & Kaye (1996) compare the light scattered from micro-machined SiO_2 high aspect ratio particles (P. H. Kaye, Micheli, Tracey, Hirst, & Gundlach, 1992) with modelled light scattering images using Ray Tracing with Diffraction on Facets (RTDF, see Chapter 2). No micrograph analysis needed to be made as the aerosolised particles were of set dimensions and known prior to aerosolisation. Other studies have been conducted to compare the spatial light scattering and the theoretically modelled scattering for particles such as urban aerosol (Aptowicz et al., 2006) and ice crystals (P. H. Kaye et al., 2008). However, no downstream filter analysis of the morphological properties of the aerosol were made.

Comparisons of other properties of aerosol have been made by Reid et al. (2003), where the aerodynamic, optical, and geometric equivalent diameters of dust were investigated. This was achieved using an aerodynamic particle sizer, an optical particle counter, and scanning electron microscope (SEM) analysis of the dust particles after filter collection. That investigation showed dissimilar size distributions across the different techniques. Dust has a complex morphology and any shape analysis made is not usually beyond that of the level of sphericity. Fibrous aerosol, however, have not been studied as extensively. As discussed in Chapter 1, instrumentation and methods involved in the detection and measurement of fibrous aerosol use a secondary mechanism for detection, such as electro-magnetic field oscillations, ensemble scattering techniques, or combinations. The detection and measurement of single fibrous aerosol using only forward scattered light has, it seems, not been thoroughly investigated.

5.2 Equipment

5.2.1 Experimental Setup

General Set-up

The experimental set-up is shown in Figure 5.1. The dry fibre samples are aerosolised into the main chamber and the pump pulls the aerosol from the chamber, through PPD2 and onto a collection filter.

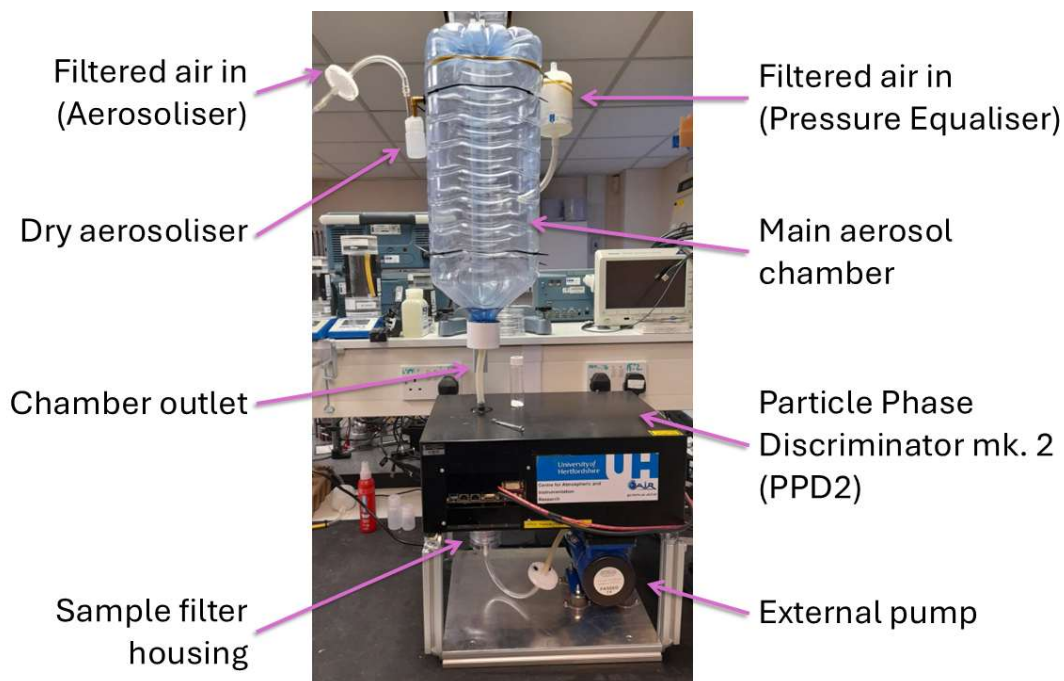


Figure 5.1: Experimental set-up.

Aerosol Chamber

The 15 L main aerosol chamber, constructed from an up-cycled water bottle, was supported by a retort stand above the PPD2 instrument⁴⁰ and connected to the inlet via a rubber hose. The top right of Figure 5.1 (labelled filtered air in) is a high efficiency particulate air (HEPA) filter for equalising the pressure created by the pump, letting clean air into the main chamber. The dry aerosoliser, shown at the top left of Figure 5.1 and in more detail in Figure 5.2, consists of an LDPE sample bottle (Thermo Scientific) with two holes in the lid. One hole is for an outlet going into the main aerosol chamber, the other is for an inlet of filtered, pressurised air. The fibre samples within the bottle were then aerosolised into the main chamber.

⁴⁰ See Section 1.3.5.

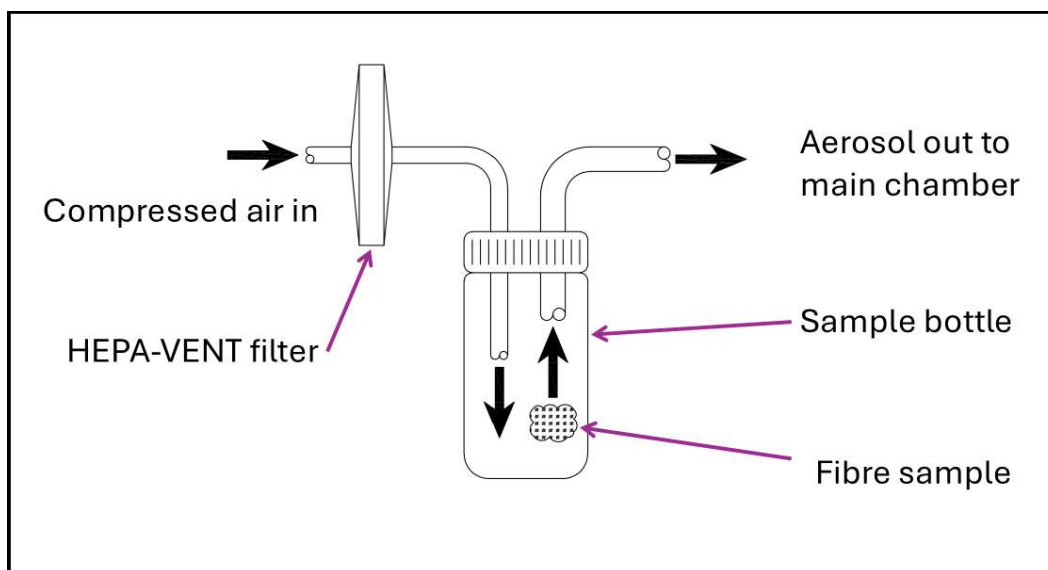


Figure 5.2: Diagram of dry aerosoliser device.

Equipment

The other equipment used for this experiment included the PPD2 instrument, an external pump (Charles Austen Pumps Ltd. SN:DT10177), an external filter housing (Pall Corp.) for 47 mm diameter polycarbonate filters (Nuclepore), a large filter for clean air into the main chamber (Whatman, HEPA-CAP), small filters on the inlets to the aerosoliser and pump (Whatman, HEPA-VENT), and a microscope (Keyence, VHX-S750E). A Gilian Gilibrator 2 (Sensidyne) was used to measure the flow rate.

Post-Collection Sample Analysis

Due to the available instrumentation, polycarbonate filters were used for the sample collection, as opposed to the micro-cellulose esters (MCEs) used in the phase contrast optical microscopy (PCOM) fibre counting methods outlined by the WHO, described in Chapter 1. After preliminary testing, the microscope used was found to be adequate for measuring the collected fibre samples, despite the use of a different filter type and procedure. The polycarbonate filters used had a pore size of $0.1\ \mu\text{m}$ and a much higher pressure-drop than MCEs and so an external pump had to be used in place of the built-in pump of the PPD2.

5.2.2 Samples

Refractory Ceramic Fibres

Refractory ceramic fibres (RCF) are based on a mixture of alumina (Al_2O_3) and silica (SiO_2) and contain a mixture of other different oxides that are added to enhance the physical properties, depending on the desired end-use (Maxim & Utell, 2018). Four different RCF samples were obtained for this experiment from Morgan Advanced Materials. Two of the samples – Superwool Plus (SP+)⁴¹ and Superwool HT (SWH) – are alkali earth silicate (AES) fibres consisting of 50 % – 82 % silica, 18 % – 43 % calcia and magnesia, and < 6 % alumina and other trace oxides. Another sample – Blanket MT2 (T1B) – was an alumino-silicate wool, consisting of 45 % – 60 % silica, 28 % – 55 % alumina, and < 18 % zirconia. The fourth sample – Alphawool HA (P36) – was a polycrystalline wool, less information on the chemical composition was given but was

⁴¹ The three-symbol abbreviations for the samples are used as a reference for the plots in Section 5.4.1.

described as alumina fibre or mullite fibre in the material safety data sheet. The intended uses for these samples were all described as some form of thermal insulation apart from the P36 sample, which had a vaguer product use description. Additionally, the P36 sample looked physically different to the others, having a “fluffy” descriptor, opposed to the grey dust appearance of the other three, as the fibres agglomerated into millimetre-sized balls⁴². Micrographs of Superwool Plus, Superwool HT, Blanket MT2, and Alphawool HA are shown in Figure 5.3, Figure 5.4, Figure 5.5, and Figure 5.6 respectively.

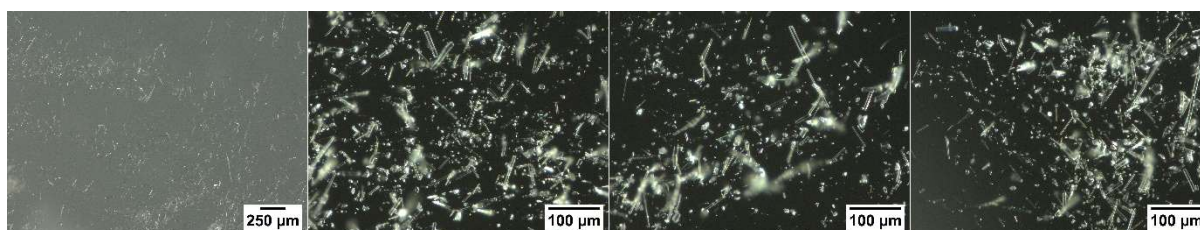


Figure 5.3: Micrographs of the Superwool Plus samples taken at 100× magnification (left) and 500× magnification.

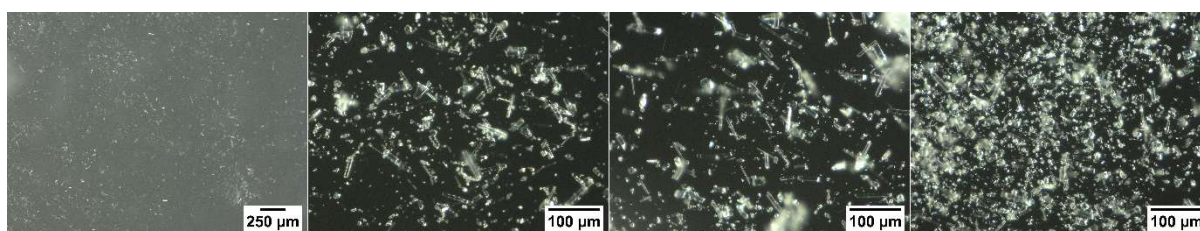


Figure 5.4: Micrographs of the Superwool HT samples taken at 100× magnification (left) and 500× magnification.

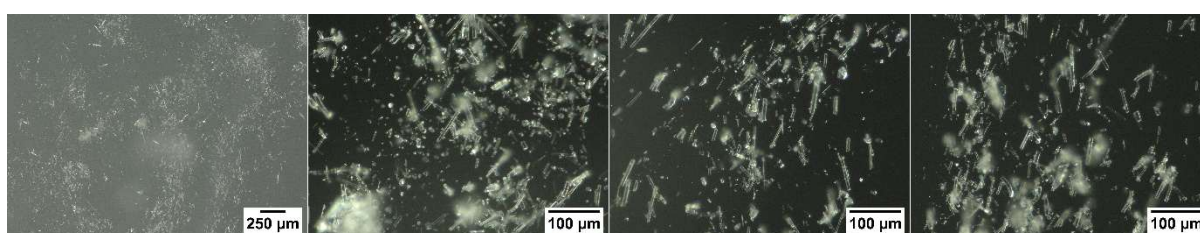


Figure 5.5: Micrographs of the Blanket MT2 samples taken at 100× magnification (left) and 500× magnification.

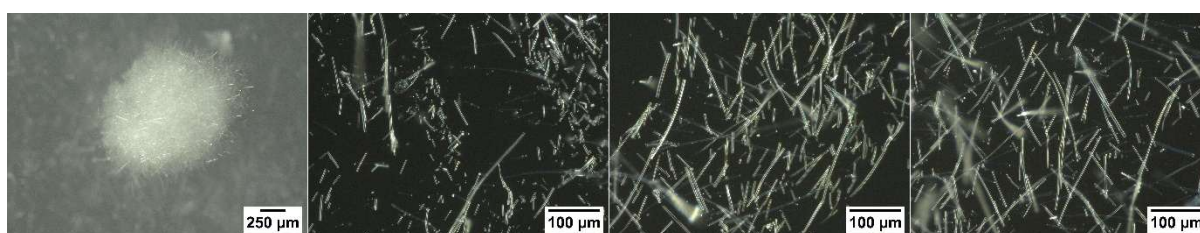


Figure 5.6: Micrographs of the Alphawool HA samples taken at 100× magnification (left) and 500× magnification.

Although each of the RCF samples look relatively similar, micrographs of each sample were still included to show they do differ slightly.

Gypsum

Another sample that was selected for aerosolisation was fibrous gypsum (GYP) that was used in the testing of the ALERT system by Stopford et al. (2013), a micrograph of the sample is shown in Figure 5.7. Gypsum is a naturally occurring mineral composed of calcium sulphate dihydrate

⁴² De-agglomeration was found to occur during the aerosolisation process.

($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and has many different commercial uses (Clouter et al., 1998) and so may be commonly found.

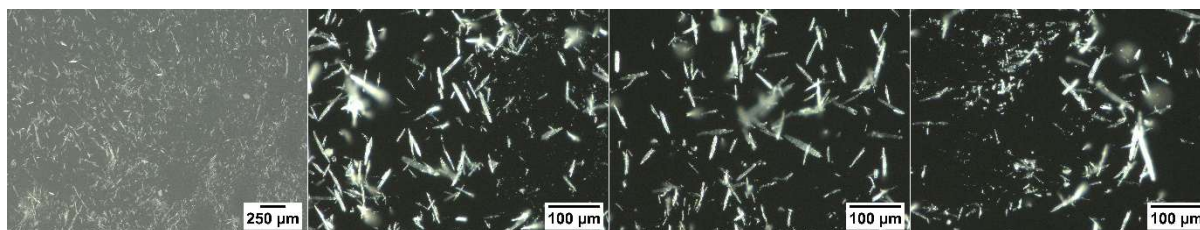


Figure 5.7: Micrograph of the gypsum sample taken at 100× magnification (left) and 500× magnification.

Wollastonite

Wollastonite (WOL) was another fibre sample obtained, used as a replacement for asbestos. Occurring both naturally and made synthetically, wollastonite consists of a calcium-silicate (CaSiO_3) and other trace oxides (Maxim & McConnell, 2005) and is used for applications such as enhancing the material properties of paint (Somtürk et al., 2016) and made into filter materials (Luyt et al., 2009). A micrograph of the wollastonite sample is shown in Figure 5.8.

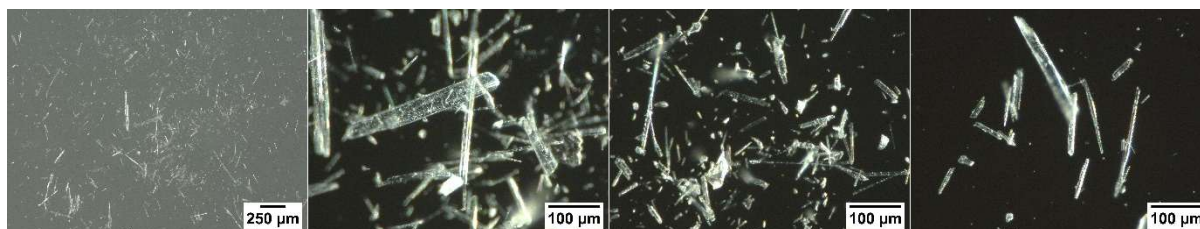


Figure 5.8: Micrograph of the wollastonite sample taken at 100× magnification (left) and 500× magnification.

Caffeine Powder

Caffeine ($\text{C}_8\text{H}_{10}\text{N}_4\text{O}_2$) powder (CAF) was also selected as a sample to be used in this experiment. The crystallisation process of caffeine results in a habit of two different crystal morphologies, one hexagonal and another fibrous, that appear to be within the respirable range (Sarfraz et al., 2012). A micrograph of the caffeine powder sample is shown in Figure 5.9.

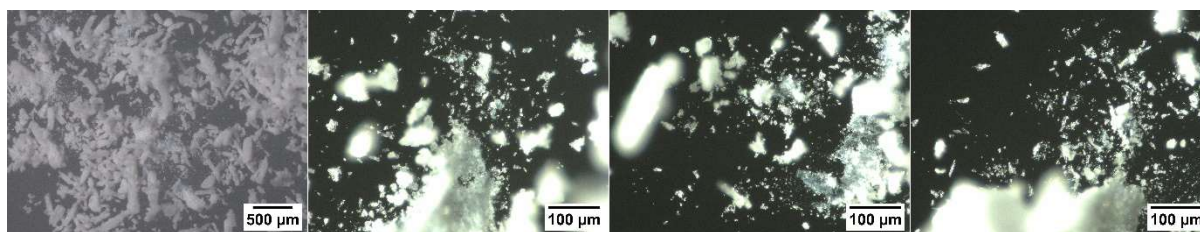


Figure 5.9: Micrograph of the caffeine powder sample taken at 100× magnification (left) and 500× magnification.

Kettle Scale Whiskers

Kettle scale whiskers (KSW) or calcium carbonate (CaCO_3) fibres were selected as the final sample to be aerosolised for this experiment. As shown in the micrograph of the sample in Figure 5.10, the fibrous structure of the sample would provide a good test sample, fairly different to those shown hitherto.

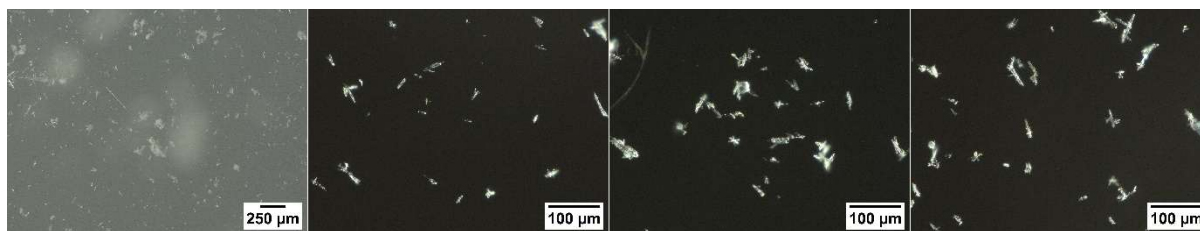


Figure 5.10: Micrograph of the kettle scale whisker sample taken at 100× magnification (left) and 500× magnification.

5.3 Method

5.3.1 Sample Aerosolisation

Aerosolising Samples

For each fibre sample, an estimated 0.2 mg was placed in the sample bottles shown in Figure 5.2. Compressed air was then sporadically applied to the inlet of the dry aerosoliser to aerosolise the fibre sample into the main aerosol chamber and to ensure the aerosol within the chamber was sufficiently homogeneous. The HEPA-VENT filter fitted between the compressed air and the dry aerosoliser helped prevent contamination from any ambient aerosol that may have been in the laboratory.

Airflow Through Instrumentation

The built-in pump of PPD2 has a flow rate of ~10 L/min, however, the pressure generated by the pump is quite low. When attempting to use the built-in pump with the collection filter in-line the flow rate was almost unreadable. To overcome the pressure-drop at the filter, a bigger diaphragm pump was used. The flow rate of the external pump was measured to be ~15 L/min dropping to ~6 L/min with the collection filter in-line which was within the operational range of the instrument. An additional HEPA-VENT filter was placed between the collection filter and the external pump to prevent any possible contamination or exposure from the aerosolised fibres. A hole in the main aerosol chamber was made and a HEPA-CAP filter fitted to allow the equalisation of pressure without any contamination of laboratory air.

Repeating the collection of scattering images and filter analysis without the inclusion of a sample, i.e., a null control, was deemed unnecessary at the time. As will be discussed in Section 5.4.1.2, some scattering images required manual removal from that dataset due to the image variation (non-fibrous, inclusions, too greater curvature, etc.) and so a baseline reading for a control set was not required. Additionally, without a particle-laden airflow there would be nothing to trigger PPD2 for data capture – unless triggered from electronic noise, as will also be discussed in Section 5.4.1.2.

5.3.2 Contamination Considerations

Aerosol Chamber

To avoid any cross-contamination of fibre samples a set of cleaning procedures were followed between each sample of the experiment. For the main aerosol chamber, the connection to the PPD2, the dry aerosoliser, and the pressure-equaliser filter were all removed. The interior of the chamber was then sprayed with water to douse any possible remaining aerosol present and clean the interior walls of any deposited sample. After rinsing the chamber was left to dry. Two chambers were made to be alternated between the cleaning and experimental processes.

Between the aerosolisation of the different samples the outer surface of the PPD2 was cleaned with isopropyl alcohol (IPA, 98%). The interior of the device was more difficult to clean since the scattering chamber is not designed to be readily accessible. However, after each day of aerosolising samples, the inlet was unscrewed and as much of the interior of the scattering chamber as possible was cleaned using IPA and a lint-free cloth.

Tools and Other Equipment

After the collection filter had been removed from the in-line filter mount, using tweezers and placed into a clean petri-dish, the rest of the equipment and tools were also cleaned. The hose connection from the main chamber to the PPD2 inlet and the top section of the dry aerosoliser were both doused with IPA to remove any possible sample deposition and left to dry. The rest of the tools and equipment, such as tweezers, sample trowel, and filter housing were then wiped down with IPA and a lint-free cloth and left to dry in a clean petri-dish.

5.3.3 Measurements

5.3.3.1 Reference Data

As described in Chapter 4, different sets of reference data were generated using the Amsterdam Discrete Dipole Approximation (ADDA) model for the different diameter measurements and the length measurements. This was done using cylinders of varying length and diameter of a refractive index of $1.8+0.8i$. The reference data⁴³ used for evaluating the size of the object that created⁴⁴ the scattering data captured by PPD2 is shown in Figure 5.11. The total method, shown in blue, are the results from using the mean value of the total scattering image, using the horizontal direction for the diameter measurements and the vertical direction for the length measurements. The section method, shown in orange in Figure 5.11, are the results from using a mean value of a section of the modelled scattering image. This is described in greater detail in Chapter 4 and in Section 5.3.3.2.

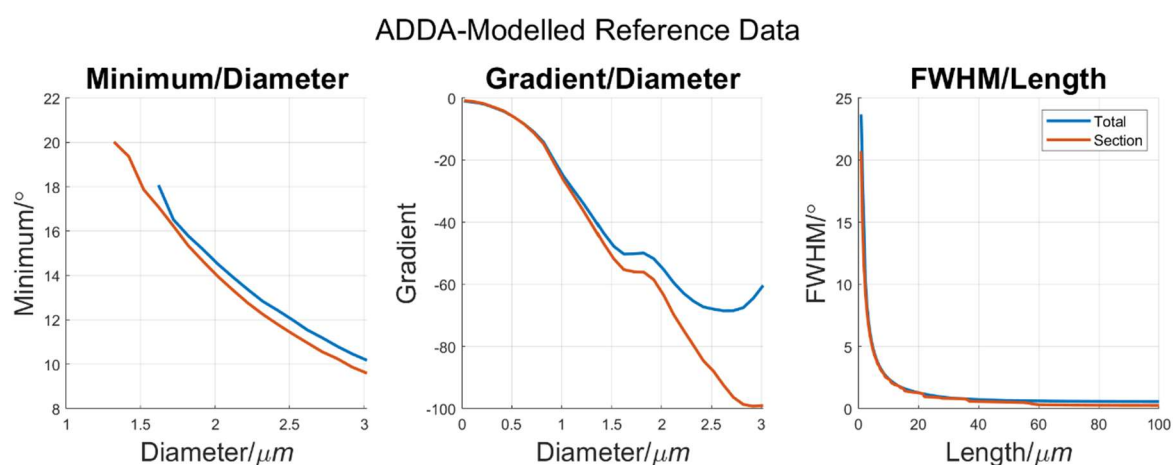


Figure 5.11: Reference data modelled using ADDA. The minimum dependence on diameter is shown in the left-hand side, the gradient of the line of best fit measured between the scattering angles of 7.25° and 9° dependence on diameter is shown in the centre, and the FWHM measurement dependence on the length is shown in the right-hand side. Each measurement was taken using a cylinder of refractive index $1.8+0.8i$ using both the total (blue) and section (orange) methods, more information can be found in Chapter 4.

⁴³ See Section 4.3.1.

⁴⁴ Will be referred to as “measuring”.

The dependence of the minimum and the cylinder diameter is shown in Figure 5.11 (left) and was used to measure the larger fibre diameter of the samples. The dependence of the gradient of a line of best fit measured between the scattering angles of 7.25° and 9° , and the diameter is shown in Figure 5.11 (centre) and was used to measure the diameter of any fibre that did not produce a minimum point in the forward 26° scattering pattern. The angular limits of the gradient measurement have changed from those discussed in Chapter 4, the reason for this change is discussed in Section 5.3.3.2. The dependence of the full-width half maximum (FWHM) value and the cylinder length is also shown in Figure 5.11 (right). All of these measurement processes have been described in greater detail in Chapter 4.

5.3.3.2 Measured Light Scattering Features

As the aerosol samples are drawn through the PPD2 instrument, individual particles pass through the sensing volume of the PPD2 and scatter the light of the focused laser. The forward 26° of scattered light passes through a set of focusing optics to an intensifier, with the scattering image finally captured by the CCD camera. A more in-depth review of the PPD2 is found in Chapter 1 and a diagram of the instrument is shown in Figure 5.12.

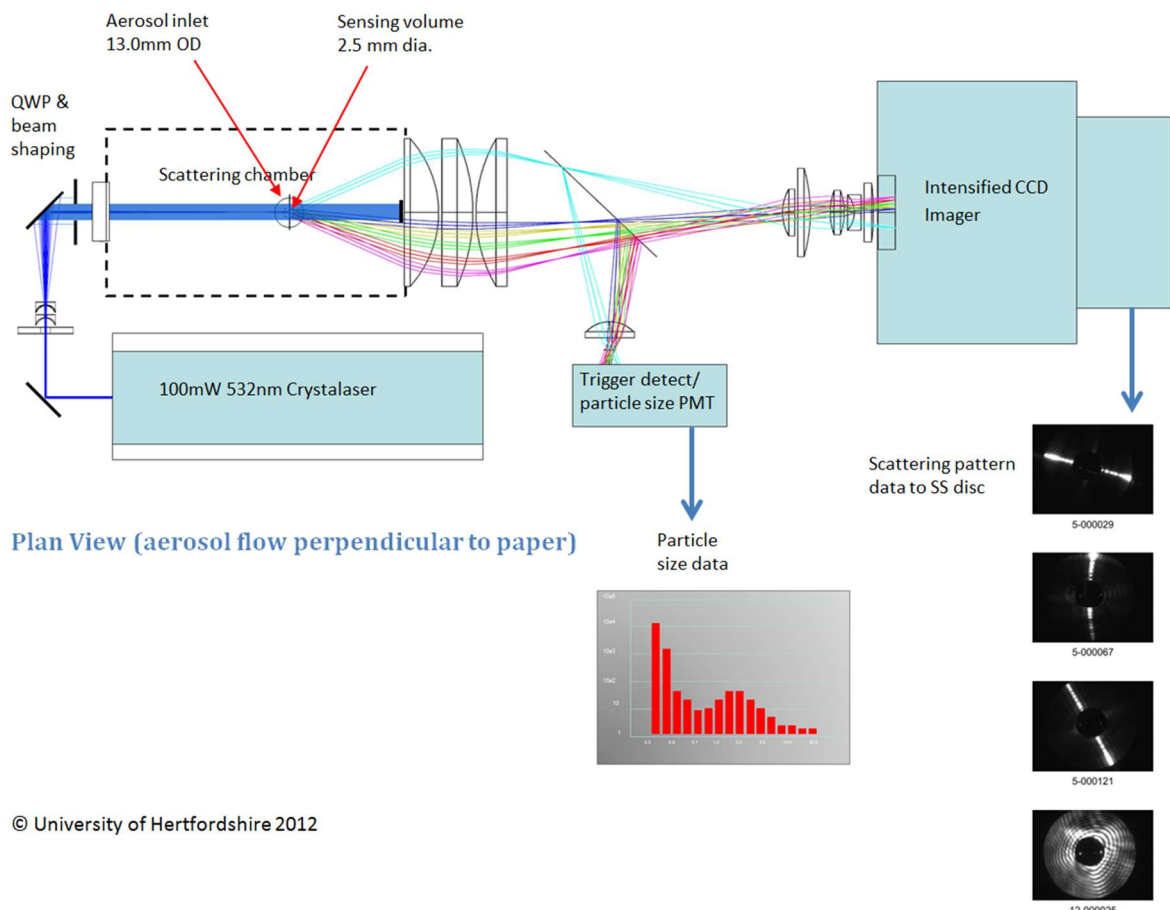


Figure 5.12: Particle Phase Discriminator mk. 2 (PPD2) inner workings diagram.

The scattering images captured by PPD2 are typically a 768 by 582 pixel bitmap image with the circular 26° forward scattering image located in the centre, an example is shown in Figure 5.13.

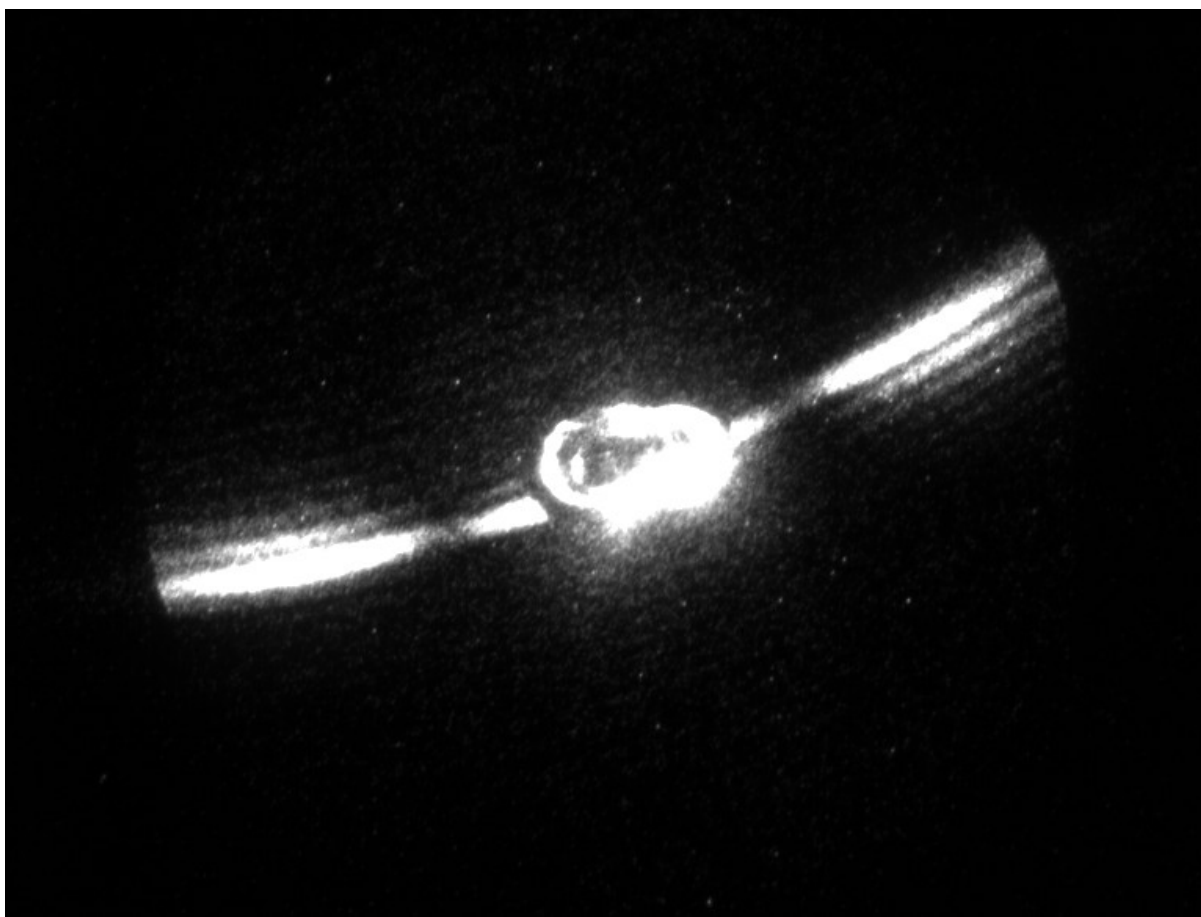


Figure 5.13: PPD2 scattering data of a refractory ceramic fibre.

Pre-processing of the images is required before any measurements are taken using the reference data. First the image is cropped to a size of 582 by 582 pixels, with the scattering data remaining in the centre. The image is then rotated to align the bright bands of the scattering vertically along the image. Further details of the image processing can be found in Appendix 7.4.1.

The measurements of the scattering data captured by PPD2 were conducted in the same way as the modelled data, analysed in Chapter 4. The measurements of each sample were saved to a separate file to be later measured using the modelled reference data. Unfortunately, the stray light scattered by the beam-stop in the centre of the image required a larger area to be covered than the 6° that was initially stated. The new angular limit of the beam-stop started at $\sim 7^\circ$ and so the optimisation of the gradient measurement process (discussed in Chapter 4) was revisited and a new limit selected. The R-squared values found in the optimisation process, similar to that in Chapter 4 but with different limits ($7^\circ - 11^\circ$ in steps of 0.25°), nevertheless showed similar results (given in Appendix 7.5). The optimised angular limits for the gradient measurement, accounting for the newly discovered limitations of the PPD2 data, were found to be $7.25^\circ - 9^\circ$.

Additionally, further measures were required to compensate for the non-pristine captured scattering images when considering the FWHM measurement related to the fibre length. The modelled data used hitherto has been an ideal scattering pattern, perfectly straight and perfectly aligned cylinders have been used. The scattering images captured by PPD2 may not all be perfect examples and be slightly misaligned or saturated which could significantly affect the

corresponding length results from the FWHM measurements. Using the current measurement techniques, the FWHM measurements for a $0.5\ \mu\text{m}$ diameter by $10\ \mu\text{m}$ long cylinder were taken using ADDA modelled data for different α and β Euler angles⁴⁵ to assess any effect of orientation.

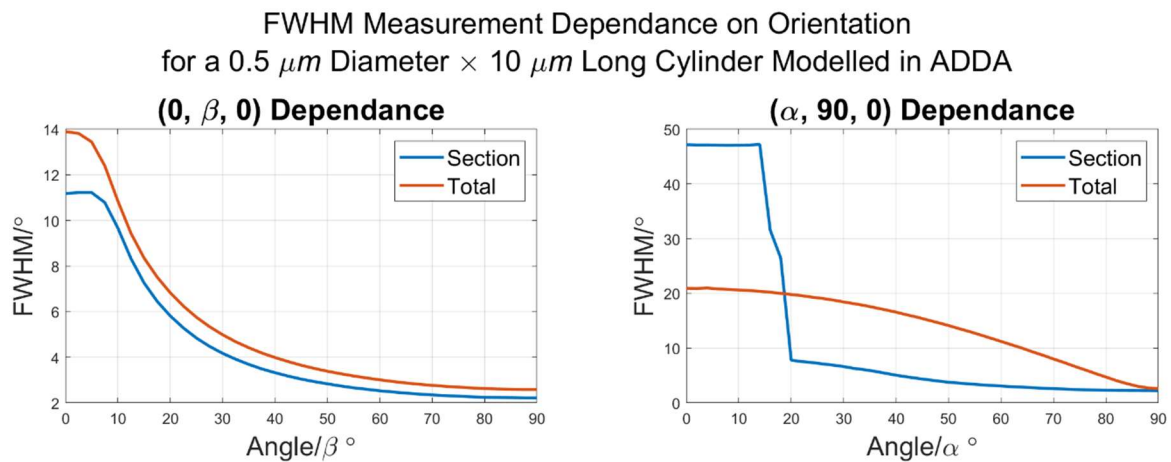


Figure 5.14: FWHM measurements of a $0.5\ \mu\text{m}$ diameter by $10\ \mu\text{m}$ long ADDA-modelled cylinder, using both the total and section techniques. Left shows the FWHM dependence on β Euler angles for $(0, \beta, 0)$ and right shows the FWHM dependence on α Euler angles for $(\alpha, 90, 0)$.

Figure 5.14 shows the results of the orientational dependence of the FWHM measurements, with the change in β Euler angle on the left and α Euler angle on the right. The α Euler angles, where 90° is the cylinder aligned horizontally (resulting in a vertical scattering band), show a much greater change in FWHM measurements, and hence length, than the β Euler angles. The large step for the section technique, shown in Figure 5.14 (right), is the result of the majority of the scattered light no longer within the section, however, the first $\sim 30^\circ$ of rotation from 90° show a much smaller change in FWHM than the total technique. All the section measurements for the FWHM have been made between the angles of $7^\circ - 11^\circ$ as these were the original angular limits for the gradient measurement prior to optimisation and became the angular limits for the section technique due to convenience. Using data modelled in ADDA, a series of FWHM measurements were made using the section technique for cylinders of a varying orientation using different angular limits to demonstrate the change in FWHM, depending on the orientation and how much of the scattering image is used. Figure 5.15 shows the results of this investigation.

⁴⁵ See Section 1.5.6 for explanation on Euler angles.

**FWHM Measurement Dependence on Orientation
for a $0.5 \mu\text{m}$ Diameter $\times$ $10 \mu\text{m}$ Long Cylinder Modelled in ADDA**

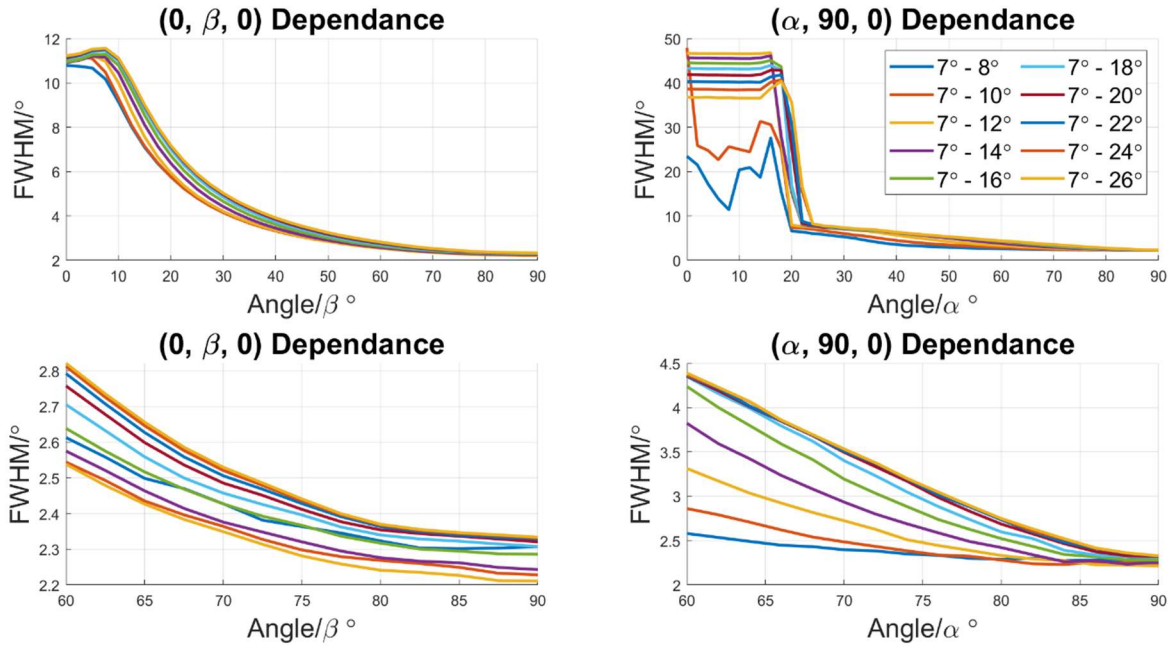


Figure 5.15: FWHM measurements of a $0.5 \mu\text{m}$ diameter by $10 \mu\text{m}$ long ADDA-modelled cylinder, changing both the β Euler angle for $(0, \beta, 0)$ (left) and α Euler angle for $(\alpha, 90, 0)$ (right), measured using the section technique of varying angular limits. The top shows the full orientational range $0^\circ - 90^\circ$ and the bottom highlights $60^\circ - 90^\circ$.

What can be deduced from the results of Figure 5.15, is that the change in β Euler angle makes less of a difference in the FWHM measurements than any change in the α Euler angle. Additionally, for the change in β Euler angle, the difference in FWHM measurements seems to be fairly proportional with the change in the angular limits of the section. The change in α Euler angle, however, shows a dependence on the angular limits of the section used; unsurprisingly showing that the smallest angular limit is the least dependent on orientation.

To account for the more chaotic nature of the PPD2 captured data, regarding the length measurements using the FWHM, a smaller angular limit of the section technique was used. Unfortunately, this was also dependant on the diameter of the cylinder. If the minimum coincided with the location of the section used to measure the FWHM, the result would not be representative. By using two sections for the FWHM measurements, realigning them and taking the mean value, this problem was ameliorated. The two new sections of $10^\circ - 11^\circ$ and $15^\circ - 16^\circ$ are highlighted in magenta in Figure 5.17.

Another issue with the PPD2 captured scattering patterns was the level of saturation of the image. The camera gain setting was adjusted, after a preliminary experiment, to best suit the fibre samples used. Unfortunately, there were still many examples of saturation in the captured data, rendering the FWHM measurements useless (as the maximum was now unknown). A measurement of the saturation was made using the angular distance the saturation occurred in the measured data, an example is shown in Figure 5.16. If the saturation was below a tolerance of 0.5° , the FWHM measurement was taken, beyond this tolerance an alternative measurement was made. Based on the diameter measurements using the minimum, a similar measurement was taken, if possible, and additional reference data was generated to find the length. The final caveat of this measurement system was that if the saturation tolerance was exceeded and either no minimum was found or the minimum of either side was deemed too asymmetrical, the

scattering data was rejected as un-measurable. The initial use of the minimum measurements for the length investigations in Chapter 2 were not considered due to how good the FWHM measurement results were.

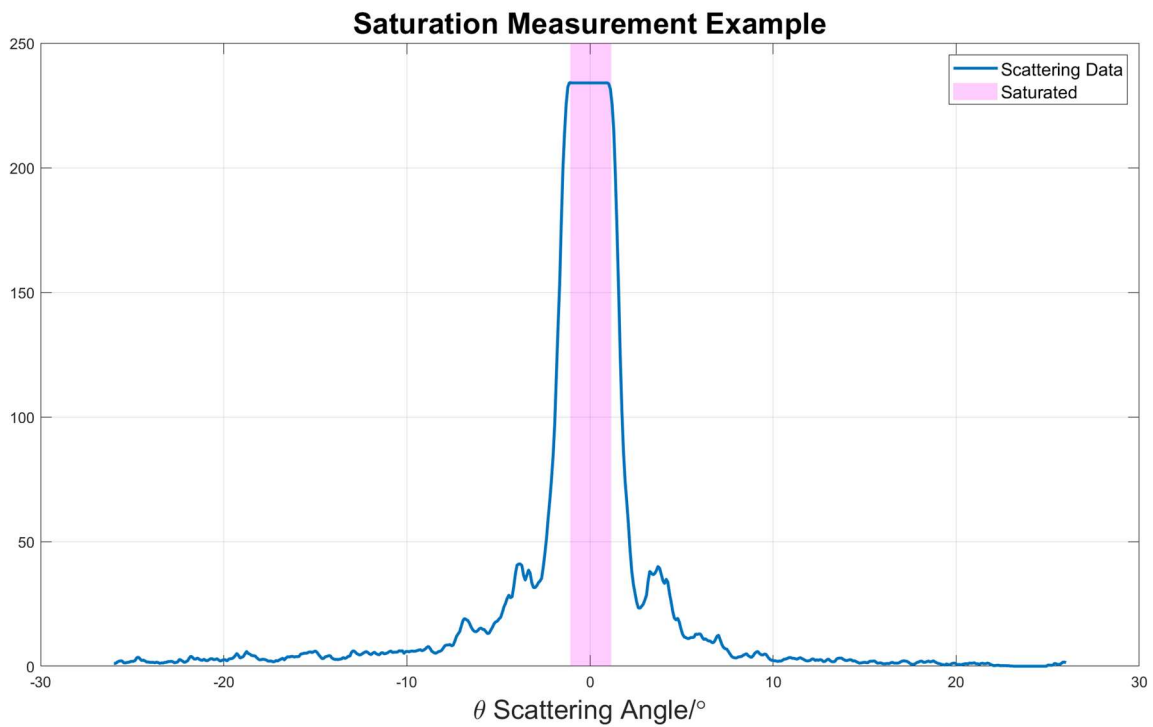


Figure 5.16: PPD2 scattering data (blue) used for length measurement as an example of image saturation, showing a 2.24° angle of saturated data highlighted in pink.

Additionally, as the PPD2 captured scattering images show a degree of asymmetry, the measurement system was used on both sides of any measurable data. The modelled data was symmetrical and did not require this. The two corresponding measurements of each side of the scattering data, were used to find a mean value and that value was then used for the measurement from the reference data.

PPD2 Scattering Analysis Example

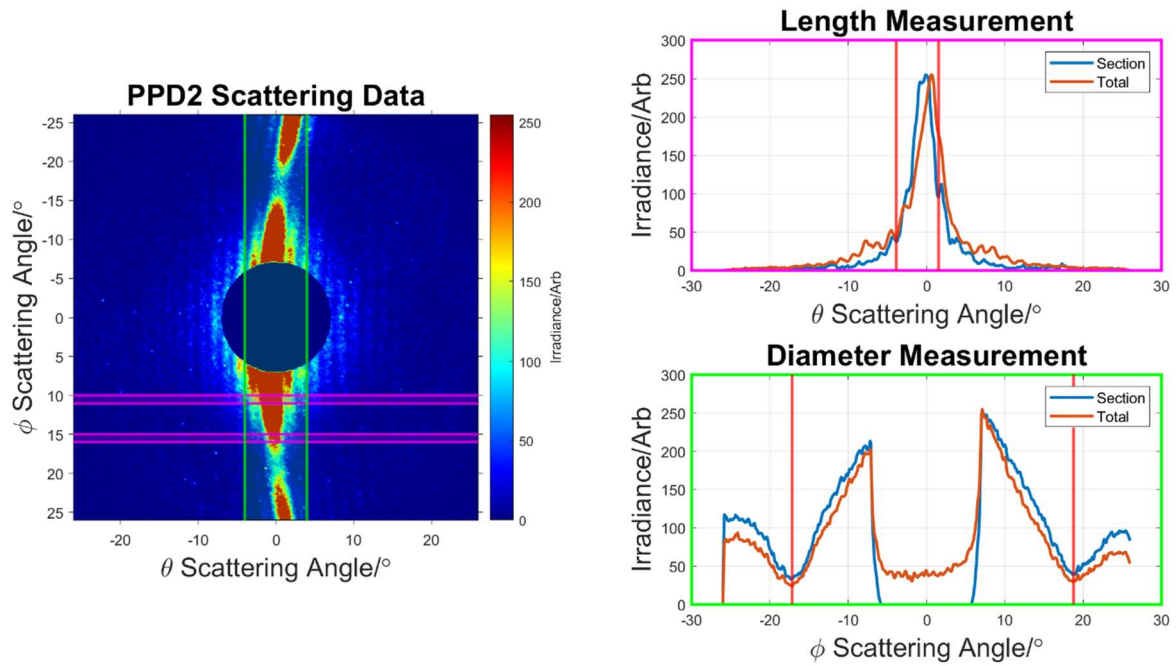


Figure 5.17: PPD2 scattering data analysis example. The image on the left shows an example of light scattered from a fibre, the green section is used for the diameter measurement (bottom right), and the magenta sections are for the length measurement (top right).

For the measurement analysis shown in Figure 5.17, this example would use the mean value of the first two minima, when considering the diameter measurement. The mean value of $\sim 17.96^\circ$, when evaluated using the reference data of Figure 5.11 from the ADDA modelled data using the section method, would give a diameter of $\sim 1.51 \mu\text{m}$.

For the length measurement, the FWHM for the section method is measured to be $\sim 3^\circ$, resulting in a length of $\sim 7.75 \mu\text{m}$. If the scattering image was saturated beyond the given tolerance, the minimum measurements could be used (Figure 5.17, top right, blue vertical lines) but not the FWHM. This example shows the minimum found on the right-hand side to be $\sim 1.5^\circ$, implying a length of $\sim 20 \mu\text{m}$. The left-hand side, however, finds the second minimum at $\sim 3.85^\circ$ due to the prominence of the first minima being below tolerance, resulting in a length of $\sim 8 \mu\text{m}$. When inspecting the scattering image (Figure 5.17, left), the left-hand side peak for the length measurement should be $\sim 2.5^\circ$, this is still very different to the right-hand side, however, the scattering image seems off-centre. Taking a mean value of these two angles and correlating the result with the reference data in Figure 5.18 gives a length of $\sim 15 \mu\text{m}$, quite different from the FWHM result and unfortunately, no means of confirming what measurement is the correct one.

The new reference data, including the alternative measurement for the fibre length, is shown in Figure 5.18. Comparing these to the previous reference data, shown in Figure 5.11, only the gradient measurements are notably different; showing an improved trend for all models and measurement techniques will provide a more reliable measurement. The alternative length measurement, using the minimum similar to the larger diameter measurements, show a monotonic trend up to $\sim 40 \mu\text{m}$. Some of the reference data will be removed, prior to the measurements, to ensure a monotonic trend.

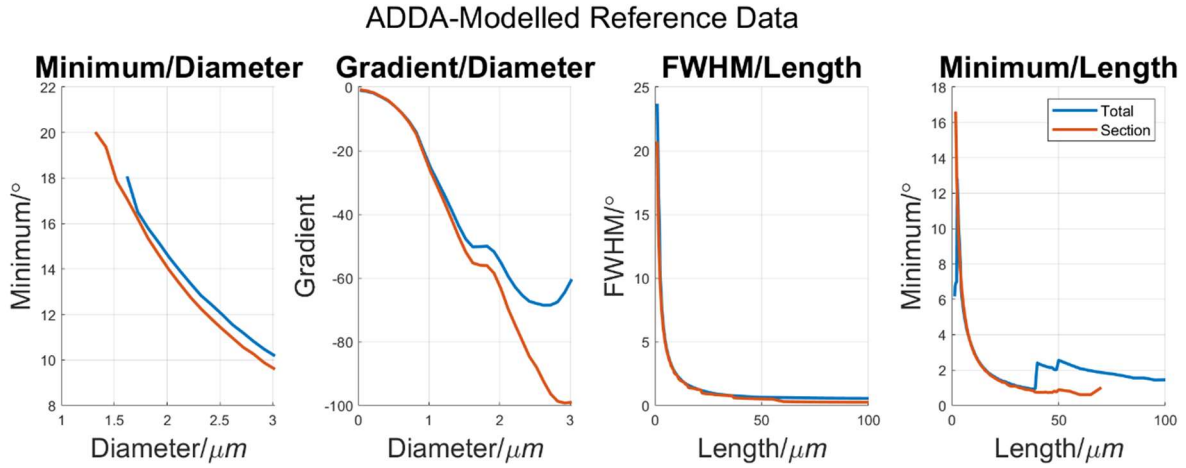


Figure 5.18: Reference data modelled using ADDA. The minimum dependence on diameter is shown in the left-hand side plots, the gradient of the line of best fit measured between the scattering angles of 7.25° and 9° dependence on diameter is shown under Gradient/Diameter, the FWHM measurement dependence on the length is shown under FWHM/Length, and the new alternative length measurement is shown on the far right. Each measurement was taken using a cylinder of refractive index $1.8+0.8i$ using both the total (blue) and section (orange) methods, more information can be found in Chapter 4.

Lastly, a discussion regarding the calibration of the PPD2 instrument is required as no actual calibration has been undertaken. What has been done is the optical layout was designed using Zemax (Ansys Inc.), where the setup resulted in the CCD camera capturing the 26° of the forward scattered light – not including the beam-stop. An experiment in clarifying this would provide additional confidence in the validity of the angular limits. A comparison between the captures scattering of the Airy disks of some aerosolised $3\text{ }\mu\text{m}$ PSL with modelled data would be a reasonably simple task, unfortunately, this was not performed due to time restrictions.

5.3.3.3 Microscopy Measurements

For each sample filter two micrographs were acquired, a small section is shown as an example in Figure 5.19. One centred in the middle of the filter and one between the middle and one edge of the filter. A magnification of $500\times$ was used to stitch a 5×5 grid of images together, totalling and area of $\sim 2.2\text{ mm}^2$. A depth function was also used, taking a series of micrographs between two set focal planes, to ensure the majority of the micrograph remained in focus.

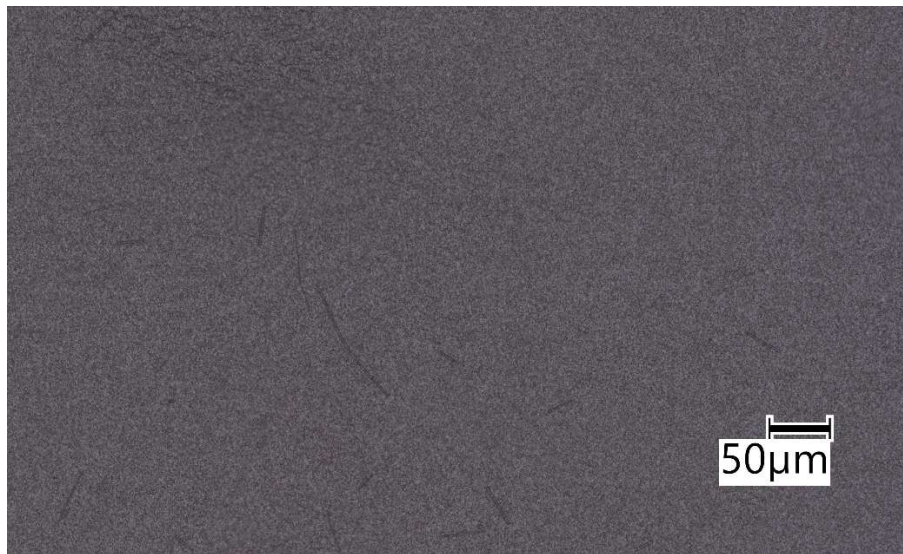


Figure 5.19: Section of micrograph from one of the refractory ceramic fibre samples.

For each sample, 200 fibres were measured from both micrographs, totalling 200 diameter measurements and 200 length measurements each. The micrographs were overlaid with a grid and the length and diameter of the fibres found were recorded after calibration using the scale bar. Each grid section was periodically examined and each fibre was numbered to avoid repeat entries and any fibres that extended beyond the edge of the image were dismissed.

The example shown in Figure 5.19 is a good representation of all the micrographs of the filter-collected fibre samples. The background noise of the micrographs were a result of the chosen filter. Attempts were made to clear the filter, i.e., render transparent, but failed. Image processing and filtering was also attempted but only resulted in further distortion of the fibres. Further details are found in Section 5.4.2.2.

5.3.3.4 Errors

Possible measurement errors have been considered and are different for each dataset and measurement technique. The errors found in the micrograph measurements are mainly due to the resolution of the micrographs. Each micrograph image measured had a resolution of ~ 5 pixels/ μm , i.e., every pixel was $0.2\ \mu\text{m}$ in length and height and corresponds to the lower diameter limit mentioned in Section 1.2.4. This had a greater effect on the smaller measurements⁴⁶, especially the diameter, where the lower edge of the smallest occupied bin boundary was $\sim 0.35\ \mu\text{m}$, attributing to around a 60% error in the diameter measurement. For the larger diameters and the length measurements, an error of $0.2\ \mu\text{m}$ is less significant.

For the scattering data, however, the possible errors are more complex. For the small diameter measurements that use the gradient, the level of noise in the image will affect the outcome of the measurement. However, due to the way the line is fitted to the data to measure the gradient, no obvious or measurable error is found. An example of the gradient measurement is shown in Figure 5.20, where the bottom right image is the scattered light, the top right plot is the data used for the diameter measurement from the section method, and the left plot is an enlargement of the green rectangle.

⁴⁶ Displayed in Section 5.4 as histograms.

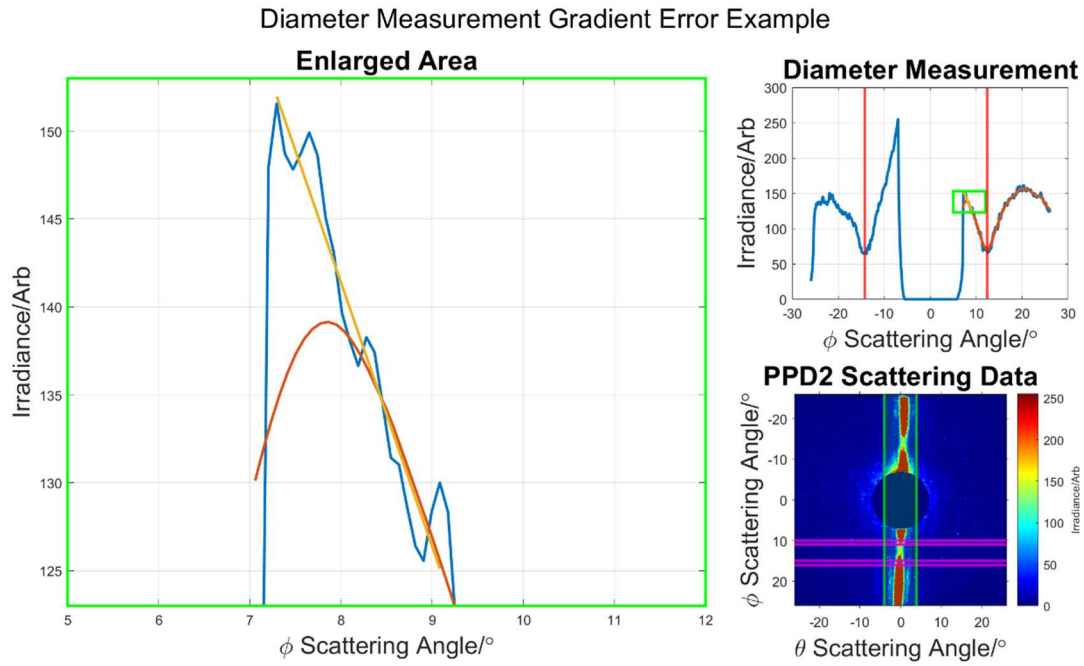


Figure 5.20: Scattering example to illustrate the possible errors found for the gradient measurements where the bottom right image is the scattered light, the top right plot is the data used for the diameter measurement from the section method, and the left plot is an enlargement of the green rectangle. The yellow line shows the fitted line for the gradient measurement, the orange line is the smoothed data, the red lines indicate the minimum locations, and the blue line is the original data.

The smoothed data is also shown in Figure 5.20 (orange) but is not used for the gradient measurement. Again, a source of error for this measurement could result from noise, however, this is not systematic and cannot be estimated.

As for the diameter measurements using the minimum, the data is smoothed using a moving average, shown as the orange line in Figure 5.20 and Figure 5.21, to prevent the noise from interfering with the minimum-finding algorithm. An enlarged example is shown in Figure 5.21, similar to the previous but for where the right-hand minimum point is found, marked using a vertical red line. The level of noise appears much greater than the gradient example, making it harder to visualise where the true minimum should be located. The smoothed data, however, does show a minimum and is marked at the right-hand side of a horizontal section of the data, i.e., the minimum is between $\sim 12.3^\circ$ and $\sim 12.4^\circ$ and is measured to be at the latter. This horizontal section attributes to a $\sim 0.09^\circ$ difference in angle and translates to around a $0.02 \mu\text{m}$ difference in diameter for this example. This difference results in a diameter measurement of $2.28 \pm 0.01 \mu\text{m}$ – roughly a 0.5% error.

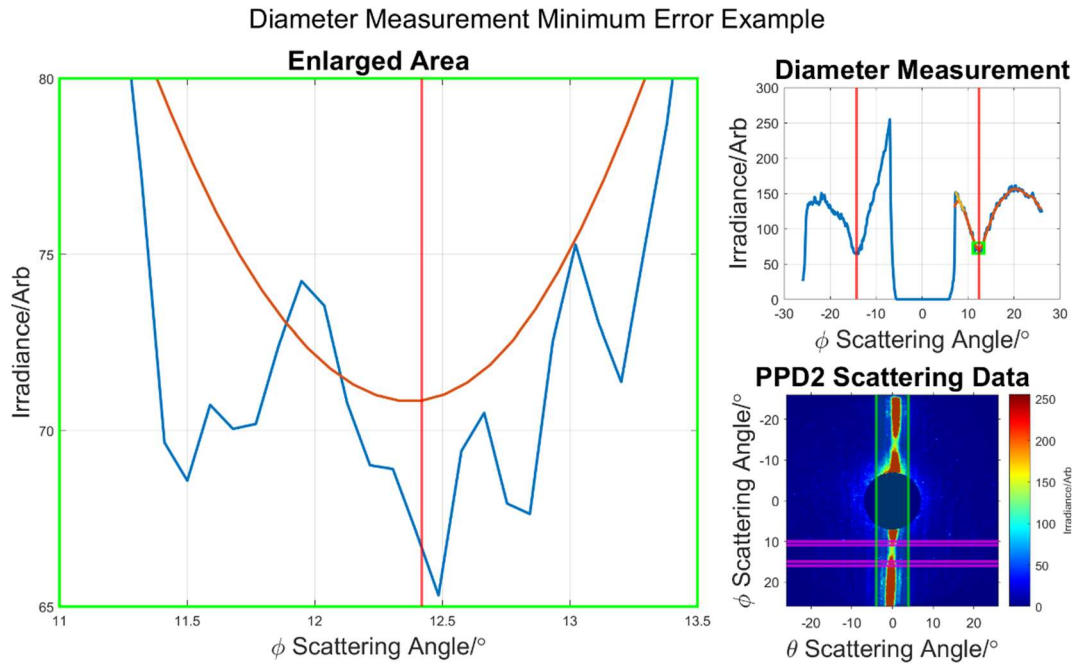


Figure 5.21: Scattering example to illustrate the possible errors found for the minimum measurements where the bottom right image is the scattered light, the top right plot is the data used for the diameter measurement from the section method, and the left plot is an enlargement of the green rectangle. The orange line is the smoothed data, the red lines indicate the minimum locations, and the blue line is the original data.

An example of the FWHM measurements for obtaining the length of the fibre is shown in Figure 5.22. The measurement of the FWHM itself shows to be accurate to the light magenta lines of Figure 5.22 (left), where the horizontal line is the half-maximum and the vertical lines mark the crossing point of the data at the half-maximum. Further enlargement of the area where these lines meet, to evaluate the accuracy of the FWHM measurement does show a slight discrepancy. However, this difference is so small that the translated length difference is not worth mentioning.

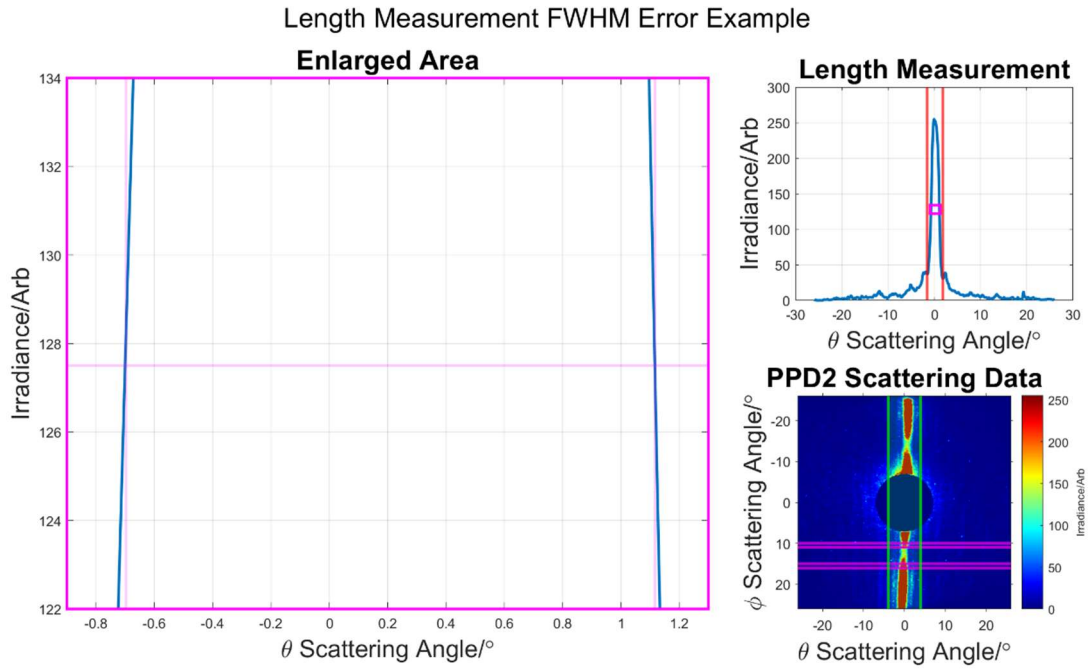


Figure 5.22: Scattering example to illustrate the possible errors found for the FWHM measurements where the bottom right image is the scattered light, the top right plot is the data used for the length measurement from the section method, and the left plot is an enlargement of the magenta rectangle. The light magenta lines indicate the half-width (horizontal) and the edges of the curve at the half-width (vertical), the red lines indicate the minimum locations, and the blue line is the original data.

When using minimum measurements for the length, however, greater errors are found in comparison to the FWHM measurements. Figure 5.23 shows an example of forward scattered light (bottom left) from a fibre, along with the processed data for the length measurement (top left), and the enlarged section of the magenta square (right). The smoothed data (Figure 5.23, top left, orange line) had to have such a small selection of points in the moving average to retain the shape of the interference pattern that additional processing was required to increase the signal to noise ratio. This was done by limiting the irradiance pixel values to 65 and smoothing the data again – tests showed slight improvements. With regards to the example shown in Figure 5.23, the difference found between the minimum of the smoothed data and that of the original is $\sim 0.05^\circ$. This translates to a difference of $\sim 0.4 \mu\text{m}$, giving a length measurement of $16.6 \pm 0.2 \mu\text{m}$, or $\sim 1.2\%$. The majority of the errors for this measurement technique, however, would be the result of the image quality due to the dynamic range of irradiance levels of the scattering pattern.

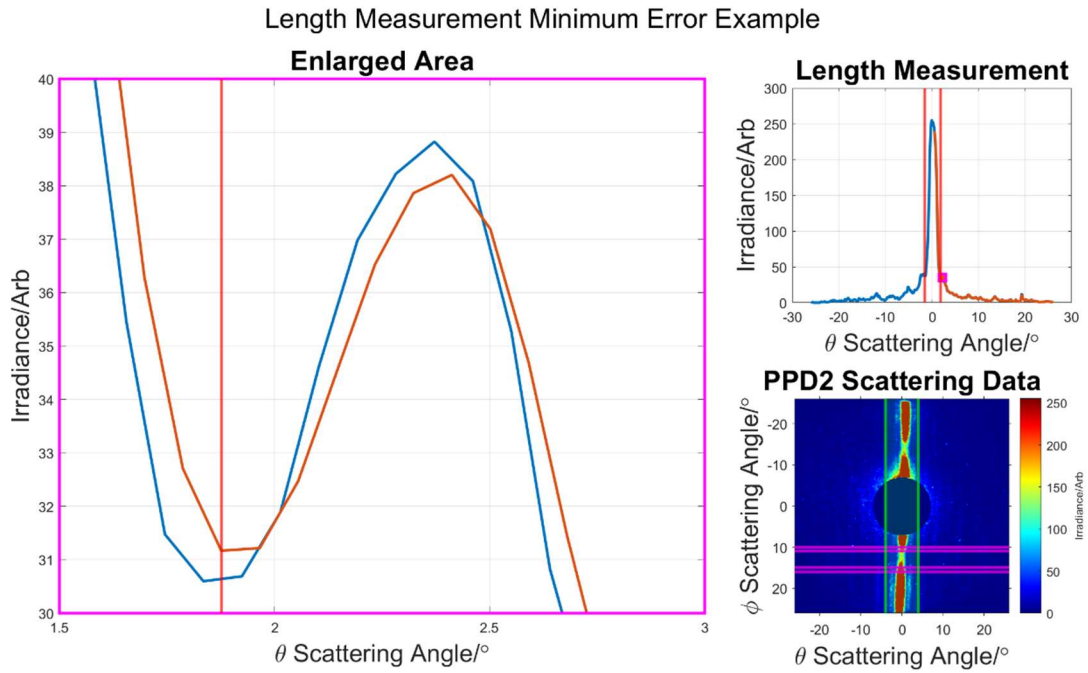


Figure 5.23: Scattering example to illustrate the possible errors found for the minimum measurements where the bottom right image is the scattered light, the top right plot is the data used for the length measurement from the section method, and the left plot is an enlargement of the magenta rectangle. The orange line is the smoothed data, the red lines indicate the minimum locations, and the blue line is the original data.

The systematic errors found in the examples show a very small change in the resulting length and diameter results for the way the scattering images are measured. An increase in image quality would allow for a more accurate measurement of these features, further reducing these errors. However, it must be acknowledged that the actual errors between the length and diameters determined from the scattered light and those of the fibre that created that scattering cannot be known, without further experimentation.

5.4 Results

The following section consists of three main parts. Section 5.4.1 shows the population distribution results of the lengths and diameters found from the light scattering patterns captured and displays them in the form of histograms. Each figure will contain the population distributions of all six samples⁴⁷ and the results of the section and total methods. Additionally, the results for the alternative length measurement are also given, where the minimum measurement is favoured over the FWHM measurement. Finally, for Section 5.4.1, there is a discussion of the problems and limitations found with the captured data and an explanation into the rejected data that includes some examples. Section 5.4.2 shows the results of the microscopy measurements for both diameter and length for all six samples, again in the form of histograms. There also includes a discussion on the problems and limitations of the micrographical analysis. Histograms of the population distribution were chosen to display the data as different sample sizes were used and a comparison between the light scattering data and microscopy data could be made. These comparisons are shown in Section 5.4.3 and display comparisons of the microscopy data and the light scattering data for any different measuring method used. This includes both the section and total methods for length and diameter and the FWHM-favoured or minimum-favoured length results. Finally, the end of

⁴⁷ Caffeine and wollastonite samples were unused, explanation given in Section 5.4.2.2.

Section 5.4.3 discusses any limitations and problems found when analysing and comparing the results.

5.4.1 Light Scattering

5.4.1.1 Analysis of Scattering Patterns

Measurements of the diameters obtained from the scattering data, using the ADDA-modelled reference data, is shown in Figure 5.24. Both the total (blue) and section (purple) techniques are included for comparison, including the median value of the data⁴⁸ – this was used as the measurement results did not seem to be normally distributed. The measurements that contained two minima⁴⁹ were first measured using the mean value of the two angles, whatever was left used the mean value of the two gradient measurements.

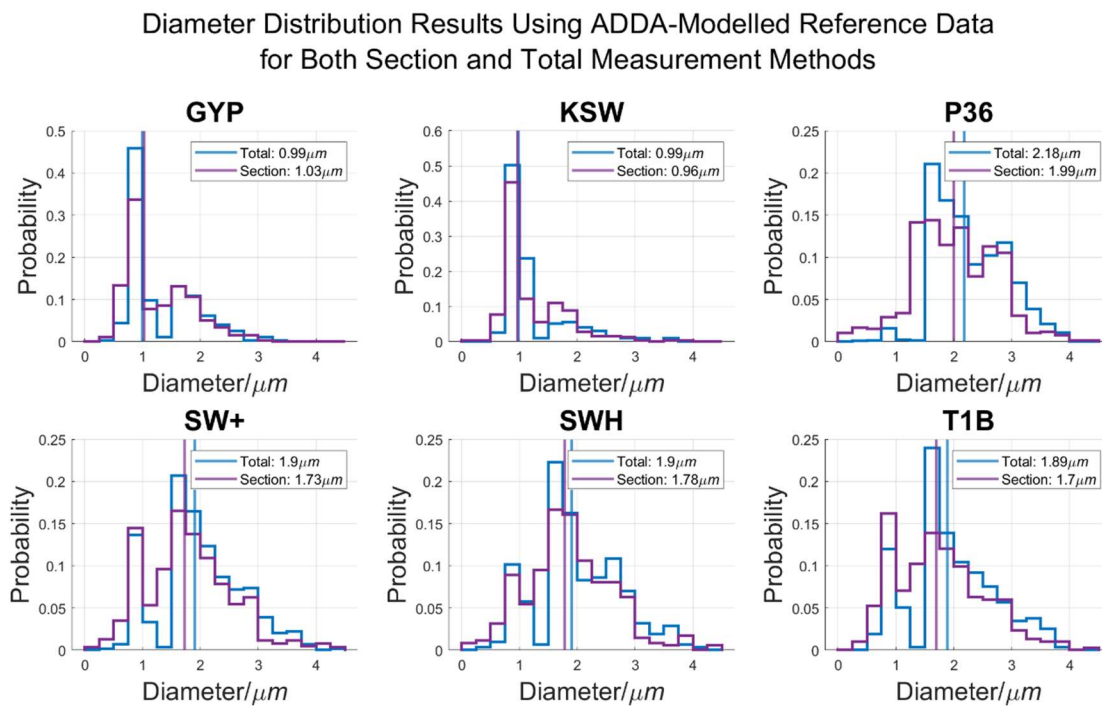


Figure 5.24: Diameter measurement results using the total (blue) and section (purple) techniques for the six selected fibre samples, measured using ADDA-modelled reference data. The median diameter is included in the legend.

The measurements for the fibre lengths were taken for any valid FWHM measurement, i.e., below the saturation tolerance, the remaining measurements were used using the valid minimum measurements. Any measurements not meeting these criteria were removed. Figure 5.25 show the length measurement results made using the ADDA-modelled reference data.

⁴⁸ Included in the figure legends.

⁴⁹ The first either side of the central peak.

Length Distribution Results Using ADDA-Modelled Reference Data
for Both Section and Total Measurement Methods Using the FWHM

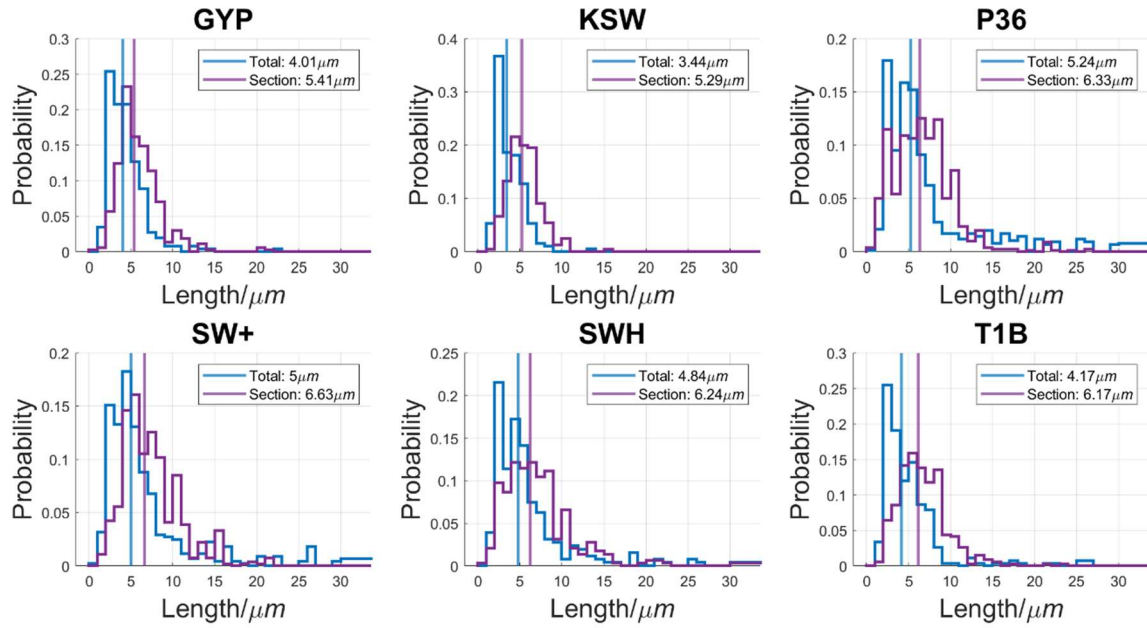


Figure 5.25: Length measurement results using the total (blue) and section (purple) techniques for the six selected fibre samples, measured using ADDA-modelled reference data. The median length is included in the legend.

An alternative length distribution was also found where the minimum measurements took priority over the FWHM measurements. Previously, the length results were made using the FWHM measurements, any scattering data not meeting the saturation conditions was then measured using the minimum, if available. Using the minimum before the FWHM showed that none of the measurements satisfied the condition in having a non-valid measurement for the minimum but with a valid measurement of the FWHM, i.e., within saturation tolerance. Therefore, the following results shown are length measured only using the minimum.

Length Distribution Results Using ADDA-Modelled Reference Data for Both Section and Total Measurement Methods Using the Minimum

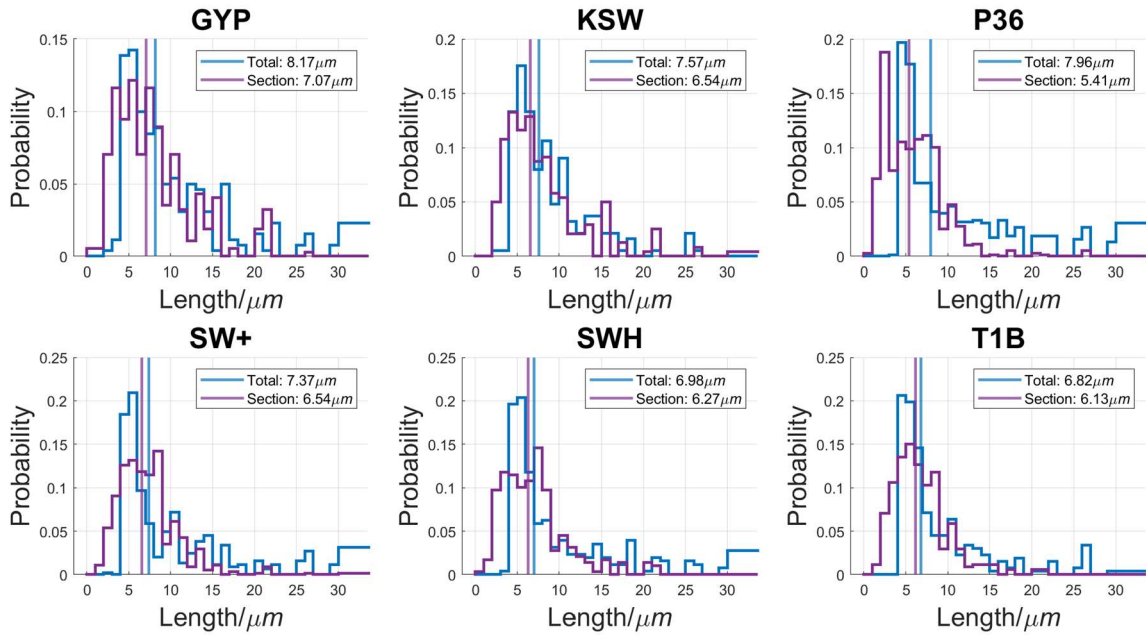


Figure 5.26: Length measurement results using the total (blue) and section (purple) techniques for the six selected fibre samples, measured using ADDA-modelled reference data and using the alternative minimum measurements. The median length is included in the legend.

For a more comprehensive analysis of the distributions in the later sections, the results of each sample will be combined. Figure 5.27 shows the results of the combined diameter measurements (left), the combined length measurements using the FWHM-dominated system (middle), and the combined length measurements using the minimum (right).

Size Distribution Results Using ADDA-Modelled Reference Data for Both Section and Total Measurement Methods

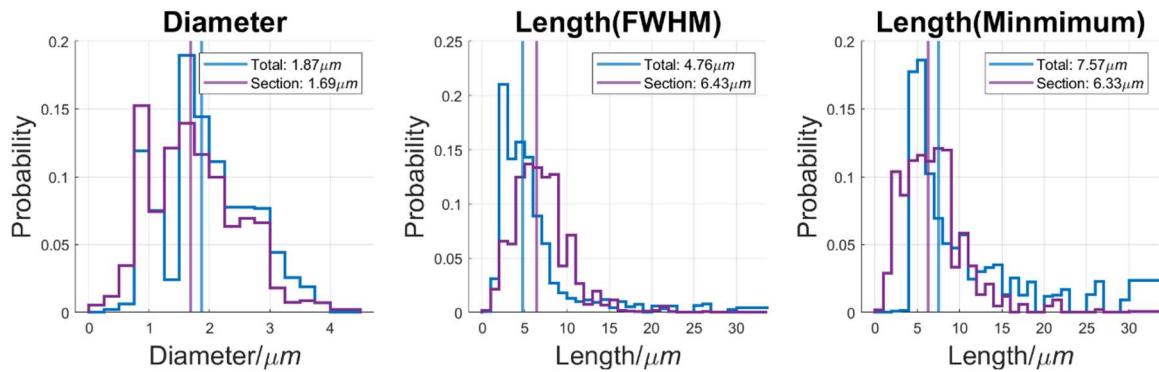


Figure 5.27: Measurement results using the total (blue) and section (purple) techniques of the combined samples, measured using ADDA-modelled reference data. Left shows the diameter distributions, middle shows the lengths measured using the FWHM-dominated system, and right shows the lengths measured using the minimum. The median size is included in each legend.

5.4.1.2 Limitations/Problems

Typical light scattering patterns from fibrous aerosol have been explored throughout this investigation and the scattering images captured by PPD2 show a promising comparison to the modelled data. Unsurprisingly, the captured scattering data is not as pristine as the modelled

data and each set also includes scattering images unsuitable for the analysis, described in Chapter 4. Examples of some of the unsuitable scattering images are shown in Figure 5.28.

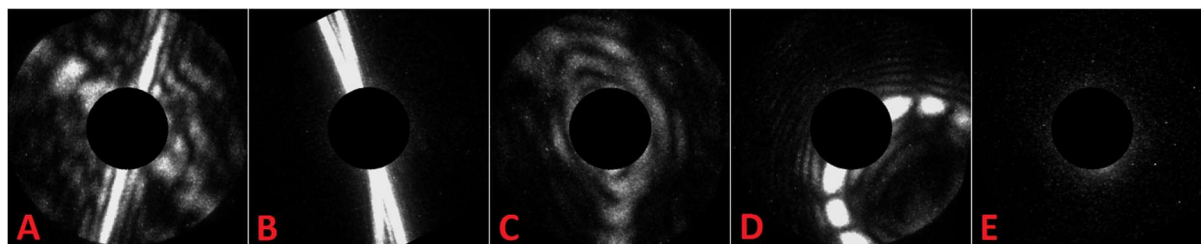


Figure 5.28: PPD2 scattering images of an agglomerate fibre, a curved fibre, amorphous dust, a fibre at an oblique angle of orientation, and the camera triggering on electrical noise (from left to right).

Scattering image A of Figure 5.28 shows an example of a fibre-dust agglomerate, the additional scattering from the dust particle interferes with the expected scattering from the fibre, making an analysis more difficult. Figure 5.28 B shows the forward scattering of a fibre that has a slight curvature, due to the bow-tie shape of the scattering a length would be impossible to measure using the current length measurement technique, as described in Chapter 4. Scattering image C of Figure 5.28 shows the light scattered from amorphous dust, a contaminant possibly sourced from the ambient lab air or mixed within the fibre samples themselves. Figure 5.28 D shows the light scattered from a fibre at an oblique angle. The curved pattern of misaligned fibres show the possibility of measurement as they display the same measurable features seen from aligned fibres, however, due to the lack of analysis and testing, they will not be included in this analysis. Finally, scattering image E of Figure 5.28 shows a “noise trigger”, where electrical noise within the instrument causes the CCD camera to capture an image of the small halo of light scattered from the beam-stop. All of these examples cannot be measured using the techniques described in Chapter 4 and so were manually removed before any measurements were taken using the reference data.

Other problems found within the experiment, that affected the scattering data, were all to do with the aerosol flow through PPD2. Compensating for the pressure-drop caused by the polycarbonate filter by using the external pump caused a pulsatile airflow, due to the diaphragmatic motion of the pump. Many attempts to dampen the effect were made unsuccessfully. Additionally, the inlet of this version of the PPD2 instrument does not incorporate a sheath flow. The combination of these issues can cause the fibrous aerosol to tumble and become impractically aligned when passing through the sensing volume and even migrate out of the flow, within the scattering chamber. The resultant scattering images can be of very obliquely aligned fibres or have shadows in the scattering image, rendering the data unsuitable for analysis.

5.4.1.3 Rejected Image Data

From the restrictions and tolerances outlined in Section 5.3.3.2, some of the scattering images rejected by the measurement system can be identified and are shown in the examples of Figure 5.29.

Scattering Image Rejection Examples Using Total Technique Using the ADDA Reference Data Set

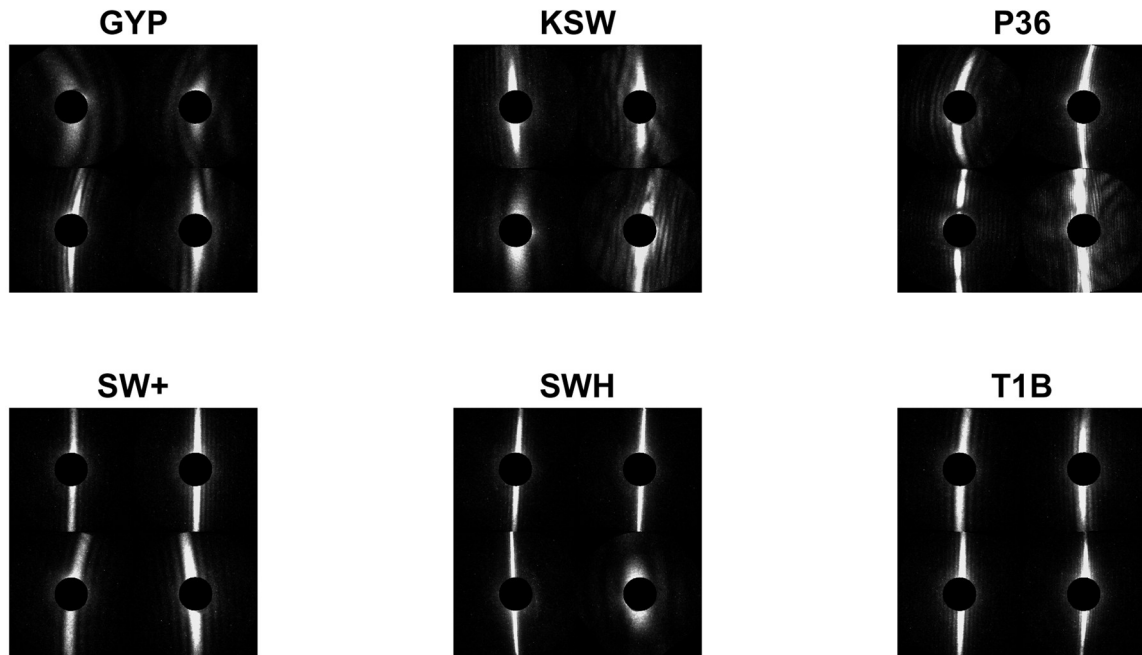


Figure 5.29: Examples of light scattering images from different samples rejected by the measurement system using the total technique and the ADDA-modelled reference data.

Many of the examples of the rejected scattering images shown in Figure 5.29 look like perfect examples of light scattered from fibres. Unfortunately, these examples show too high a level of saturation to be confidentially measured using the current measurement techniques and methods, described in Section 5.3.3.2. The less perfect-looking examples were also rejected because of over-saturation. The non-saturated rejection examples (top row of GYP, bottom left of KSW, bottom right of SWH), however, may have been rejected from a mismeasurement. If any of the measurements taken from the PPD2 scattering images are beyond the limits of that measurement in the reference data, then there is a possibility for a gross over- or under-sizing to occur.

5.4.2 Optical Microscopy

5.4.2.1 Sample-Typical Size Distributions

Diameter distributions of the six remaining samples found from the micrographs are shown in Figure 5.30.

Diameter Distribution Results from Micrograph Data

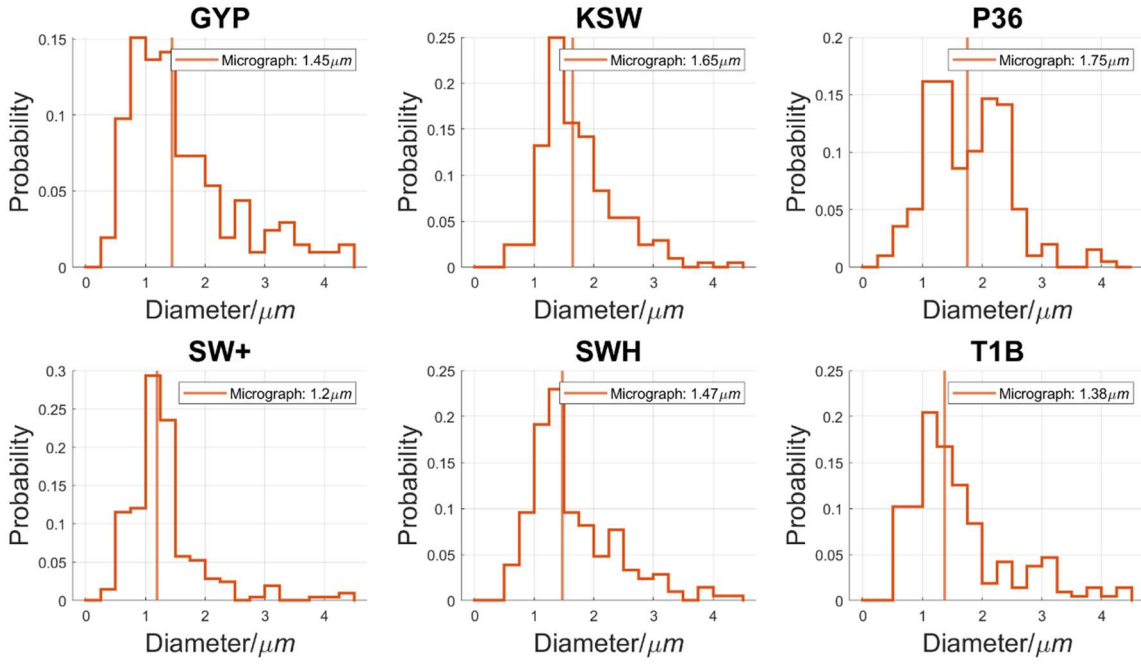


Figure 5.30: Micrograph results showing the probability distributions of the measured diameters of the collected fibre samples.

Similarly, probability distributions of the length measurements for the micrograph data are shown in Figure 5.31.

Length Distribution Results from Micrograph Data

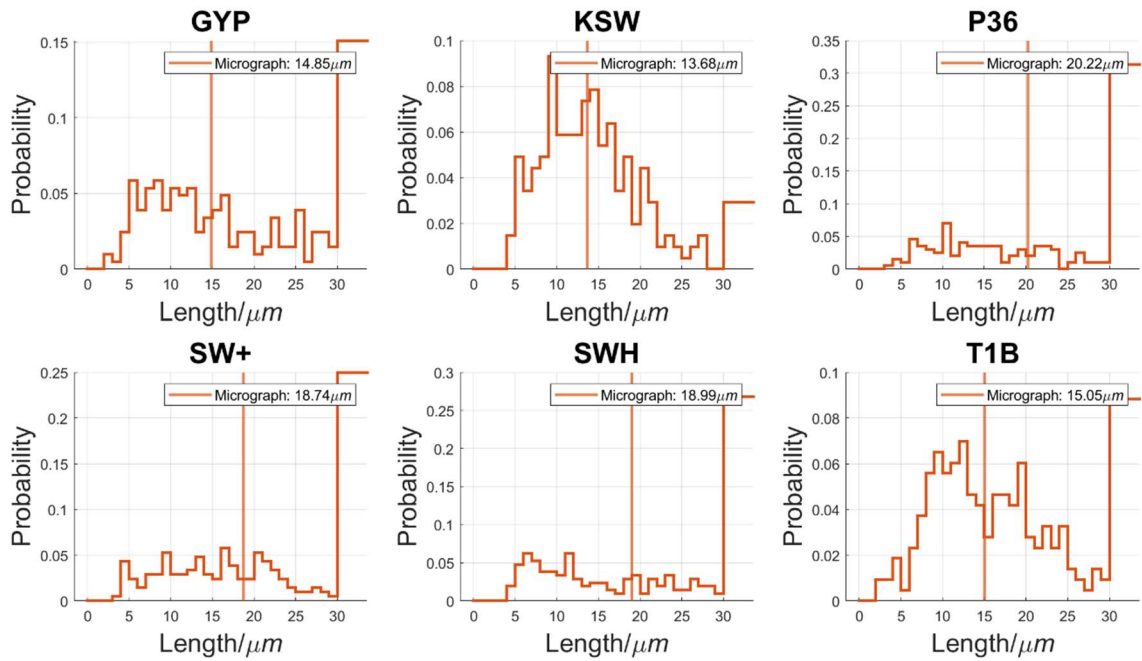


Figure 5.31: Micrograph results showing the probability distributions of the measured lengths of the collected fibre samples.

Length measurements larger than $30\mu\text{m}$ have been binned together, due to the sparse count of fibres with lengths $> 30\mu\text{m}$.

Similarly to the results of Section 5.4.1.1, the distributions have been combined and are shown in Figure 5.32.

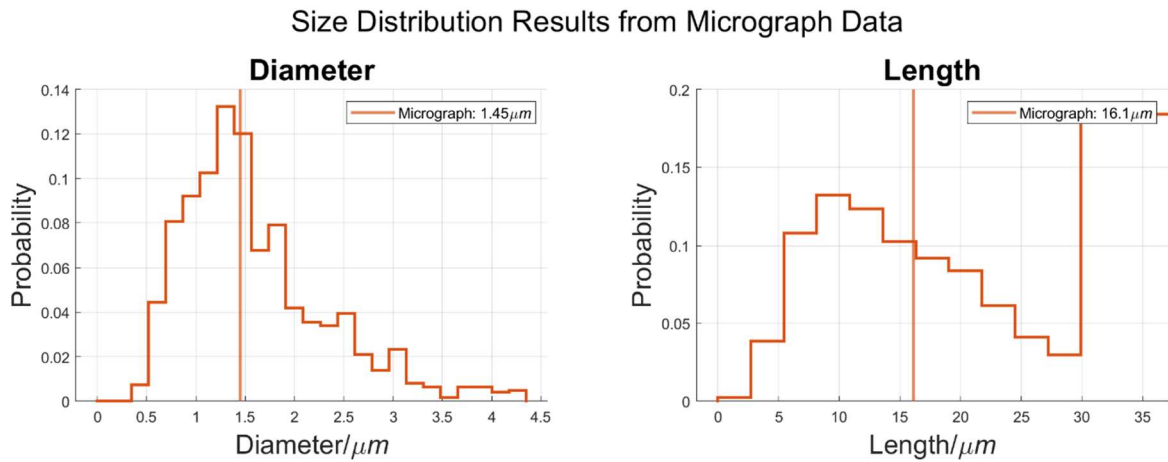


Figure 5.32: Micrograph results showing the probability distributions of the measured diameters (left) and lengths (right) of the combined collected fibre samples.

5.4.2.2 Limitations/Problems

As shown in the micrograph example in Figure 5.19, the texture of the filter caused problems in the micrograph analysis. Many attempts were made to remove or filter the background texture using different image filtering and background reduction techniques. Unfortunately, each attempt only made the definition between the fibres and the background worse and so no automated measurements could be made. Additionally, only ~90 fibres were found from micrographs of the wollastonite sample and none for the caffeine sample and so were not included in the rest of the investigation.

Prior to the micrograph analysis, attempts at “clearing” (rendering transparent) the polycarbonate filters were made using filters populated with standardised Arizona test dust. Both water and a water/detergent mix at 2% were used, both with and without coverslips over the sample filter. The tests showed little improvement and also created micro-bubbles to further obscure the micrograph images, as shown in Figure 5.33. The petri-dishes were also put in a pressure chamber, in an attempt to remove the micro-bubbles. However, even after an hour little difference was found.

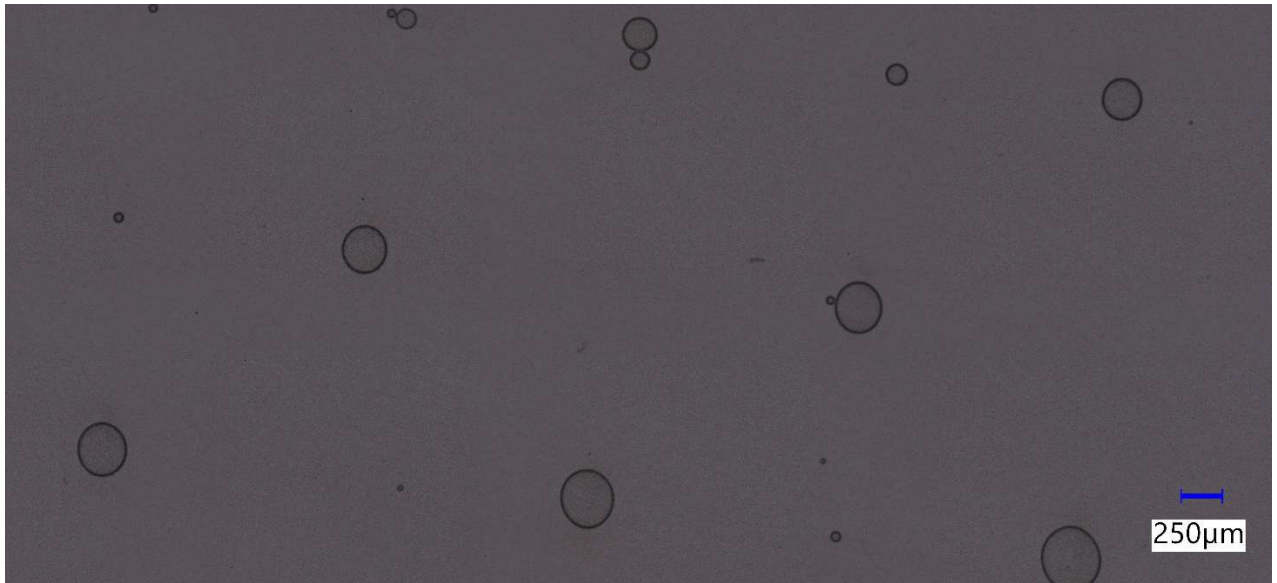


Figure 5.33: Micrograph section example of test dust sample during clearing attempt.

5.4.3 Comparisons

A visual comparison of the percentage size distributions between the data measured from the scattering patterns and the data measured from the micrographs, including their errors, will be shown in this section. To avoid confusion the results of the different measurement techniques (section and total) will be displayed in separate plots.

5.4.3.1 Diameters

Figure 5.34 shows both the micrograph diameter measurements and the scattering measurements using the section method (right) and the total method (left), made using the ADDA-modelled reference data.

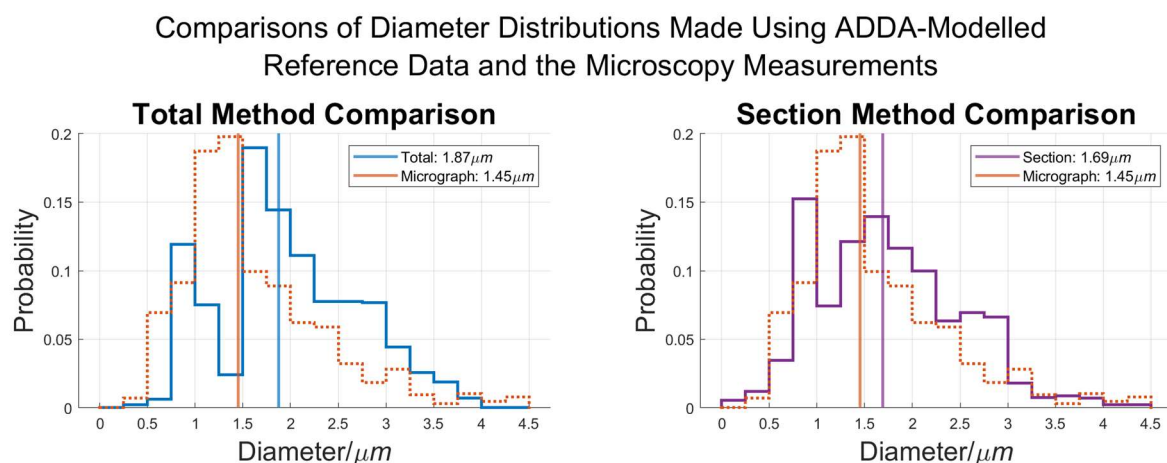


Figure 5.34: Comparisons of the diameter size probability distributions of the micrograph data (dashed orange line) and the diameter measurements of the scattering data using the section technique and the ADDA-modelled reference data. The median diameter is included in the legend.

Visually, aside from the difference found between 1 μm and 1.5 μm , the distributions show reasonable similarities to the micrograph data. A better match is found for the section data, indicated both by the distribution and the closer match of the median diameter value.

5.4.3.2 Lengths

Figure 5.35 shows the length probability size distribution comparisons of the micrograph data and the ADDA-modelled reference data measurement results using the section technique.

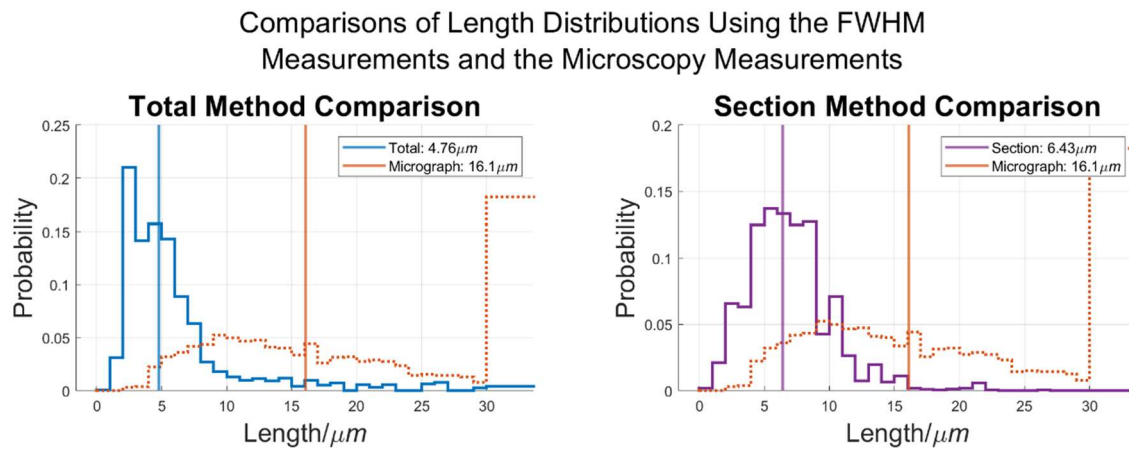


Figure 5.35: Comparisons of the length size probability distributions of the micrograph data (dashed orange line) and the length measurements of the scattering data using the section method (right) and the total method (left). The median length is included in each legend.

When comparing the results from the measurements taken using the minimum the distributions, shown in Figure 5.36, a mild improvement from the FWHM is noticed. The median value of the length found from the scattering data has increased from a value of $\sim 5 \mu\text{m}$ to $\sim 7 \mu\text{m}$, indicating a shift to a higher value in the distributions and fitting better with the micrograph data. The distributions still unfortunately show a poor match.

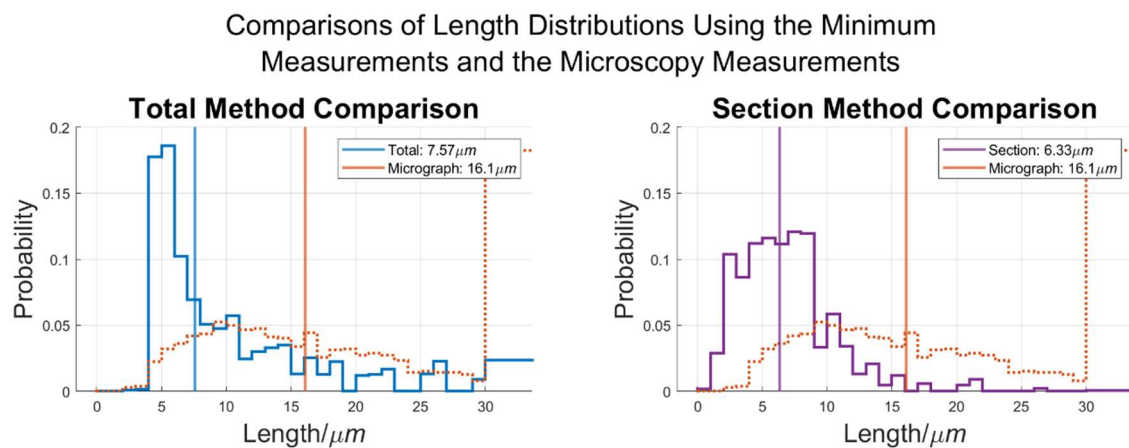


Figure 5.36: Comparisons of the length size probability distributions of the micrograph data (dashed orange line) and the length measurements of the scattering data using the section method (right) and the total method (left), made using minimum measurements. The median length is included in each legend.

5.4.3.3 Limitations/Problems

After the removal of data that did not meet the criteria, outlined in Section 5.3.3.2, only a percentage of the total data for each sample remained. This was anywhere between $\sim 20\%$ and $\sim 75\%$ of the total scattering images of each sample, totalling $\sim 40\%$ of the combined scattering data. Additionally, many images were removed prior to the measurements, as explained in Section 5.4.1.2. The sensitivity of these criteria showed to be an issue; lowering the tolerance of the saturation levels did show an improvement in the length probability distributions, however, this also drastically decreased the total number of useable image data.

On further investigation of the diameter measurement results, that resembled an almost bi-modal distribution, a better evaluation of the gradient and minimum measurements was made. The dip in this bi-modal distribution occurs, for most of the diameter results, around $1.5\ \mu\text{m}$ and this coincides with the transitional point of the reference data from using the gradient measurement and the minimum measurement. The measured scattering data was separated according to the method of measurement and the micrograph data was separated by a diameter of $1.62\ \mu\text{m}$. This value was chosen since, from the reference data showed in Figure 5.18, it was the smallest diameter that could be measured using the minimum and the largest diameter that could be measured using the gradient measurement before the data became non-monotonic. The results for the small ($< 1.62\ \mu\text{m}$) diameters are shown in Figure 5.37 and the results for the large diameters ($\geq 1.62\ \mu\text{m}$) are shown in Figure 5.38.

Comparisons of Small Diameter Distributions and Microscopy Measurements

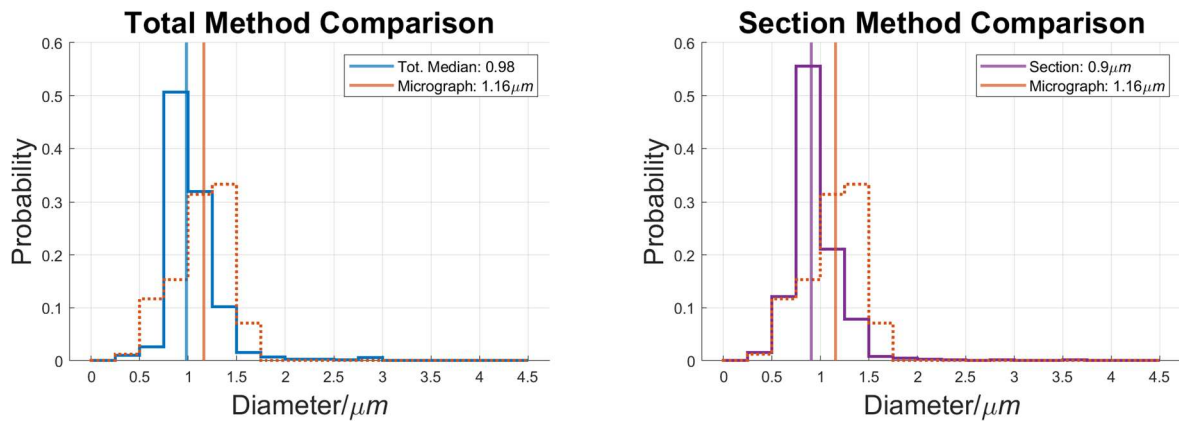


Figure 5.37: Comparisons of the diameter size probability distributions of the micrograph data (dashed orange line) and the diameter measurements of the scattering data using the section method (right) and the total method (left) for diameters $< 1.62\ \mu\text{m}$. The median diameter is included in each legend.

On visual inspection of Figure 5.37, the median diameters and general distribution seem shifted to a smaller diameter, indicating an under-sizing of measurements. The larger diameters (shown in Figure 5.38) however, show more promising results. This indicates that the diameter measurements using the minimum are more reliable than those using the gradient method.

Comparisons of Large Diameter Distributions and Microscopy Measurements

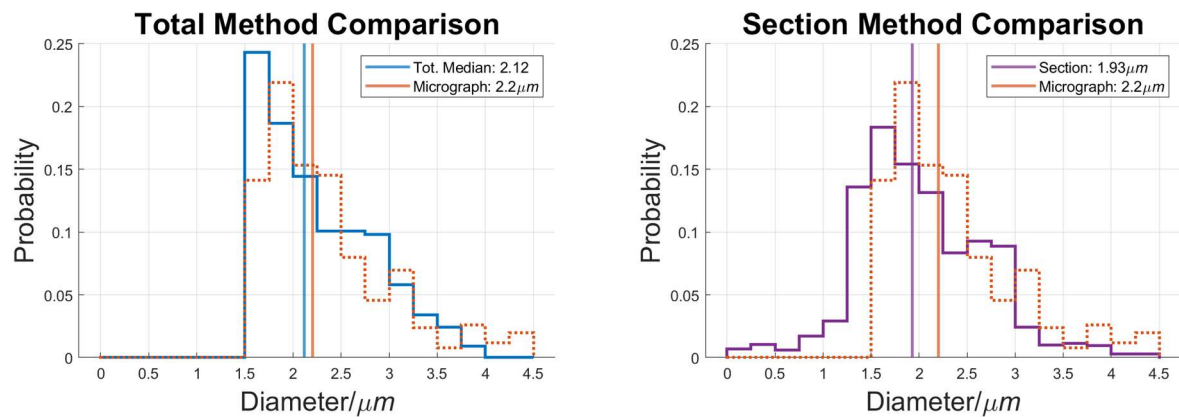


Figure 5.38: Comparisons of the diameter size probability distributions of the micrograph data (dashed orange line) and the diameter measurements of the scattering data using the section method (right) and the total method (left) for diameters $\geq 1.62\ \mu\text{m}$. The median diameter is included in each legend.

To visually confirm the algorithm is functioning adequately for the diameter measurements, randomly selected scattering images were taken from different ranges of diameters and are shown in Figure 5.39. Rows from the top to the bottom represent the diameter ranges of $< 0.7 \mu\text{m}$, $0.7 \mu\text{m} \leq 1.4 \mu\text{m}$, $1.4 \mu\text{m} \leq 2.1 \mu\text{m}$, $2.1 \mu\text{m} \leq 2.8 \mu\text{m}$, and $> 2.8 \mu\text{m}$ respectively.

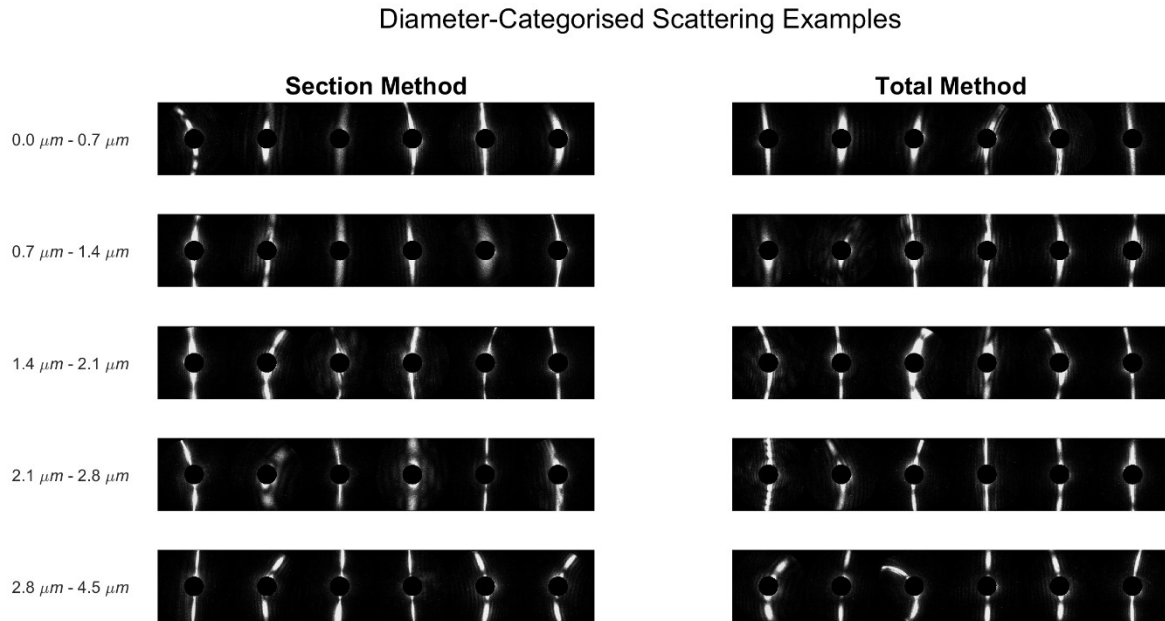


Figure 5.39: Scattering image examples from different diameter ranges for the section method (left) and the total method (right).

Generally, as the diameters increase, the minima are found to move closer to the centre of the image. There are, however, exceptions and could be explained by the band curvature created through orientation, the method of measurement, or a combination of both.

A limitation of the length results for the scattering data may have occurred from the size of the beam focus; any fibre length greater than this that would extend beyond the edges would show the same length from the scattering pattern. Additionally, due to the greater variation in size found with the fibre lengths, compared with the variation in diameters, the sample size may have been inadequate for a statistically significant population distribution.

To assess the different methods of length measurement visually, similarly to the diameters of Figure 5.39, examples of scattering images were taken from different ranges of lengths using the FWHM measurement and are shown in Figure 5.40. Rows from the top to the bottom represent the length ranges of $< 2 \mu\text{m}$, $2 \mu\text{m} \leq 4 \mu\text{m}$, $4 \mu\text{m} \leq 5 \mu\text{m}$, $5 \mu\text{m} \leq 7 \mu\text{m}$, and $> 7 \mu\text{m}$ respectively.

Length-Categorised Scattering Examples Using the FWHM Measurements

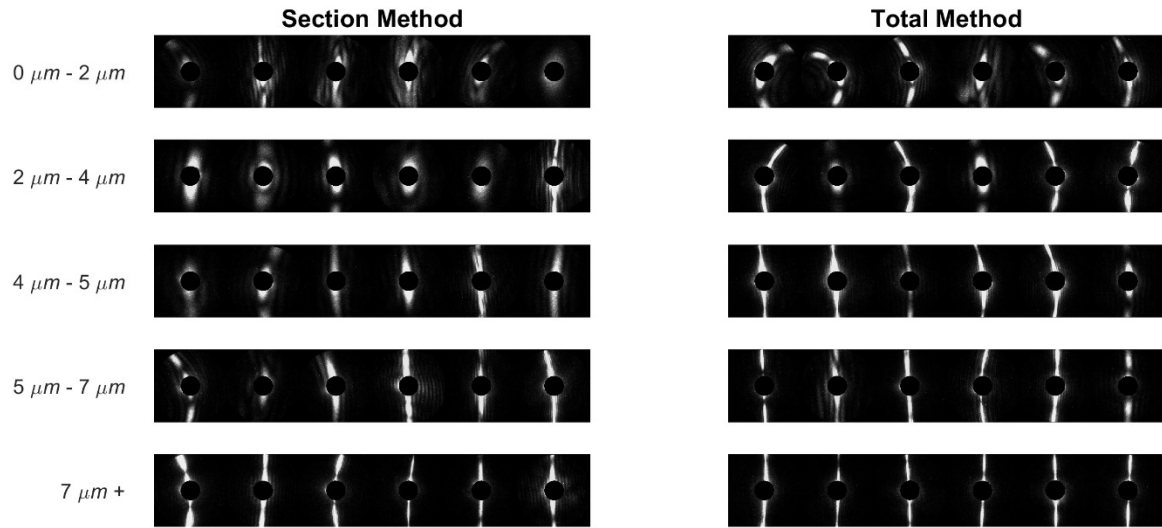


Figure 5.40: Scattering image examples from different length ranges measured using the FWHM for the section method (left) and the total method (right).

With increasing length, the scattering images display a narrowing of the bright band, as expected and shows the measurement algorithm works. Examples of the length measurements made using the minimum are shown in Figure 5.41 – no data was found for lengths $< 2\ \mu\text{m}$ using the total method.

Length-Categorised Scattering Examples Using the Minimum Measurements

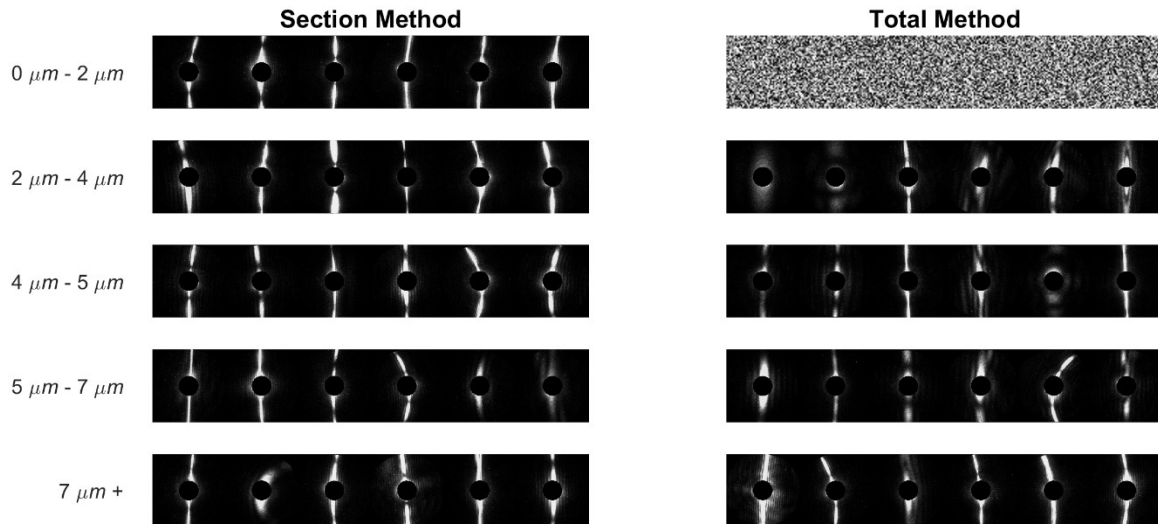


Figure 5.41: Scattering image examples from different length ranges measured using the minimum for the section method (left) and the total method (right). No data was found for $0\ \mu\text{m} - 2\ \mu\text{m}$ lengths of the total method.

Unfortunately, despite the slight improvement to the distribution comparisons in Figure 5.36, the example images shown in Figure 5.41 show a mix of scattering patterns. This is most likely

due to the minimum finding function locating noise rather than a true minimum, indicating the need for further refinement.

To further assess the performance of these measurement techniques, some captured scattering data was individually observed⁵⁰. After the measurement was made, the length and diameter was then used to model the light scattered from a cylinder of those dimensions. Figure 5.42 shows the scattering of a single fibre, captured by PPD2, randomly chosen from the data set used in this chapter. The analysis of this image (shown in the top middle and top right of Figure 5.42) concluded with dimensions of $\sim 1.8 \mu\text{m}$ in diameter and $\sim 11 \mu\text{m}$ in length. Mean values⁵¹ of the minimum for the section and total methods were found to be $\sim 15.86^\circ$ and $\sim 17.06^\circ$ respectively; $1.8 \mu\text{m}$ was found to be a good compromise. The minimum points found on the modelled equivalent were found to be $\sim 15.54^\circ$ for the section method; none were found from the total method most likely due to the prominence of the minima. As the image was not saturated the FWHM measurement was used for the length, the total method found a corresponding length of $\sim 10 \mu\text{m}$, and the section $\sim 12 \mu\text{m}$; a compromise was made for demonstration. For the PPD2 image the FWHM measurements were $\sim 2.0^\circ$ and $\sim 2.4^\circ$ for the section and total methods respectively. What was measured from the modelled data was a FWHM of $\sim 2.4^\circ$ for both. Unfortunately, if the minimum was used to measure the length the result would have been around half of what was found using the FWHM. Additionally, visual inspection of the scattering images is reassuring as both look similar. Other examples, similar to Figure 5.42, are included in Appendix 7.6 to show different lengths and diameters.

⁵⁰ Additional examples can be found in Appendix 7.6.

⁵¹ From the right and left side of the scattering data.

PPD2 Captured Scattering Data Comparison with a
1.8 μm Diameter by 11 μm Long Cylinder Modelled in ADDA

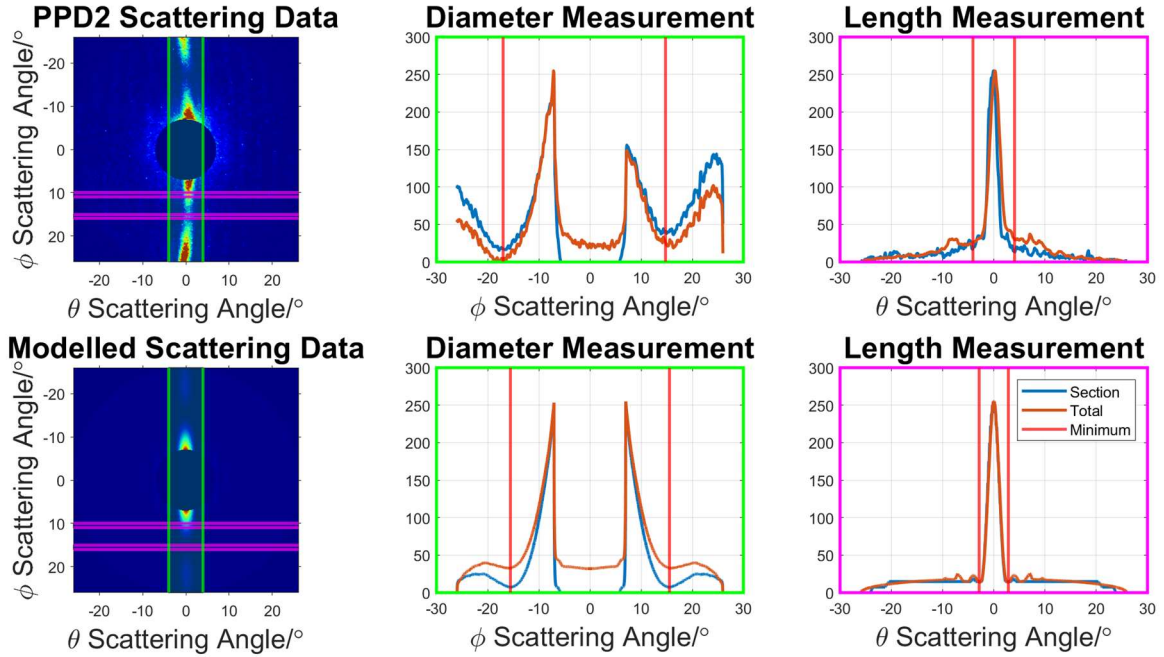


Figure 5.42: PPD2 scattering data (top row) showing the forward scattering image with marked sections (left), the scattering data used for the diameter measurements (middle), and the scattering data used for the length measurements (right). The red vertical lines indicate the minimum. The bottom row shows the same analysis of the scattering modelled by ADDA of a 1.8 μm diameter by 11 μm long cylinder that were the dimensions obtained from the top row.

Further Optimisation

Due to the investigations into the individual scattering pattern analysis, it became apparent that the minimum measurements for the length are unreliable. The signal to noise ratio is too small to sufficiently smooth the data and retain features for an adequate measurement of the minimum. An additional process⁵² was included in the processing of the data to accommodate the length measurements using the minimum whereby the scattering image was limited to a maximum pixel⁵³ value of 65 before being rescaled. This increased the signal to noise ratio and allowed for the retention of the scattering features after smoothing to accommodate for noise. Additionally, after the re-processing of the data, the Freedman-Diaconis rule was used to optimise the bin widths of the histograms:

$$W = 2 \frac{IQR(x)}{\sqrt[3]{n}}$$

where W is the bin width, $IQR(x)$ is the inter-quartile range of the sample (x), and n is number of observations in the sample. The re-processed length distributions are shown in Figure 5.43.

⁵² This has not been implemented for the FWHM measurement results.

⁵³ A maximum pixel value for the scattering data before processing is 255.

Comparisons of Length Distributions Using the Minimum Measurements and the Microscopy Measurements

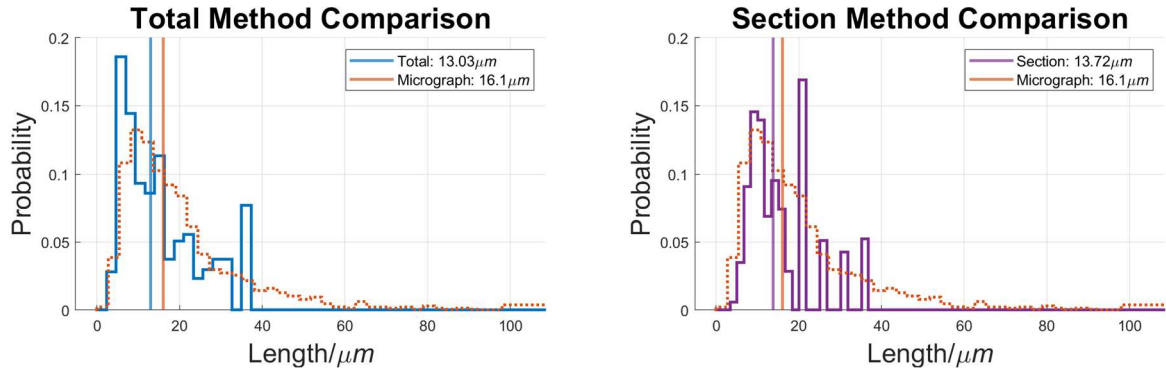


Figure 5.43: Comparisons of the length size probability distributions of the micrograph data (dashed orange line) and the length measurements of the scattering data using the section method (right) and the total method (left), made using minimum measurements after further optimisation. The median length is included in each legend.

Visually, the results show a vast improvement in matching the micrograph length distribution and the median values are also closer when compared to Figure 5.36. The lack of data for the scattering measurements beyond a length of $\sim 36 \mu\text{m}$ can be explained with the reference data. Figure 5.18 (right) shows the minimum/length relationship and the data beyond $\sim 36 \mu\text{m}$ becomes non-monotonic and is therefore removed before being used in the analysis.

Unfortunately, when using the FWHM measurements for length determination, the results show a much poorer fit after bin width optimisation, shown in Figure 5.44. This is contrary to what was shown as examples in Figure 5.41 and the FWHM measurements were expected to be an improvement.

Comparisons of Length Distributions Using the FWHM Measurements and the Microscopy Measurements

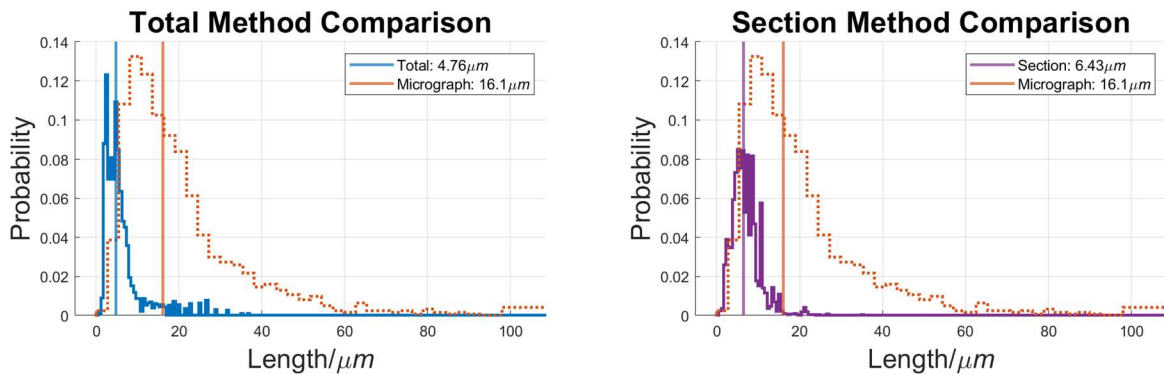


Figure 5.44: Comparisons of the length size probability distributions of the micrograph data (dashed orange line) and the length measurements of the scattering data using the section method (right) and the total method (left), made using FWHM measurements after further optimisation. The median length is included in each legend.

As to the reasoning behind the vast differences between Figure 5.43 and Figure 5.44, the most likely explanation is due to saturated scattering images. As larger particles scatter more light, longer fibres may be excluded from FWHM measurements.

The diameter measurements have not been altered, nonetheless, due to the optimisation of the bin widths the representation of the data has changed, but not by much.

Comparisons of Diameter Distributions Made Using ADDA-Modelled Reference Data and the Microscopy Measurements

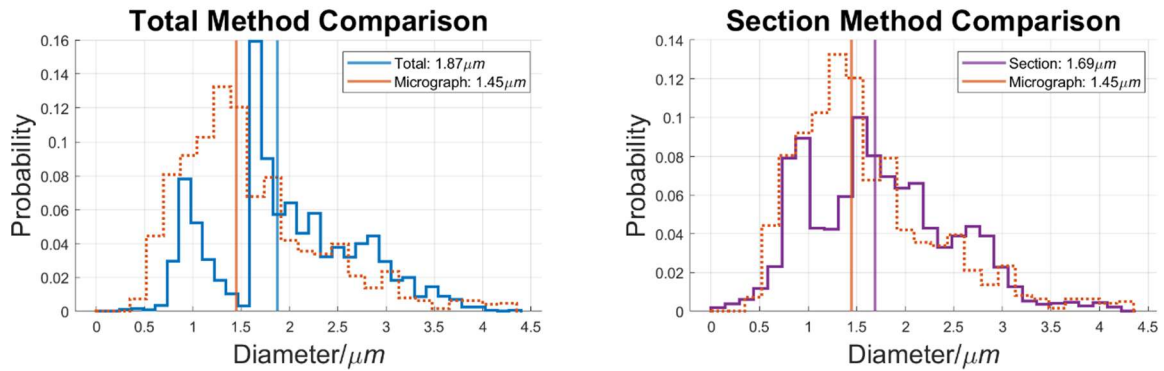


Figure 5.45: Comparisons of the diameter size probability distributions of the micrograph data (dashed orange line) and the diameter measurements of the scattering data using the section technique and the ADDA-modelled reference data with optimised bin widths. The median diameter is included in the legend.

Examples of categorised length data, after the improvement of the signal to noise ratio, similar to those shown in Figure 5.41, are given in Figure 5.46.

Length-Categorised Scattering Examples Using the Minimum Measurements After Optimisation

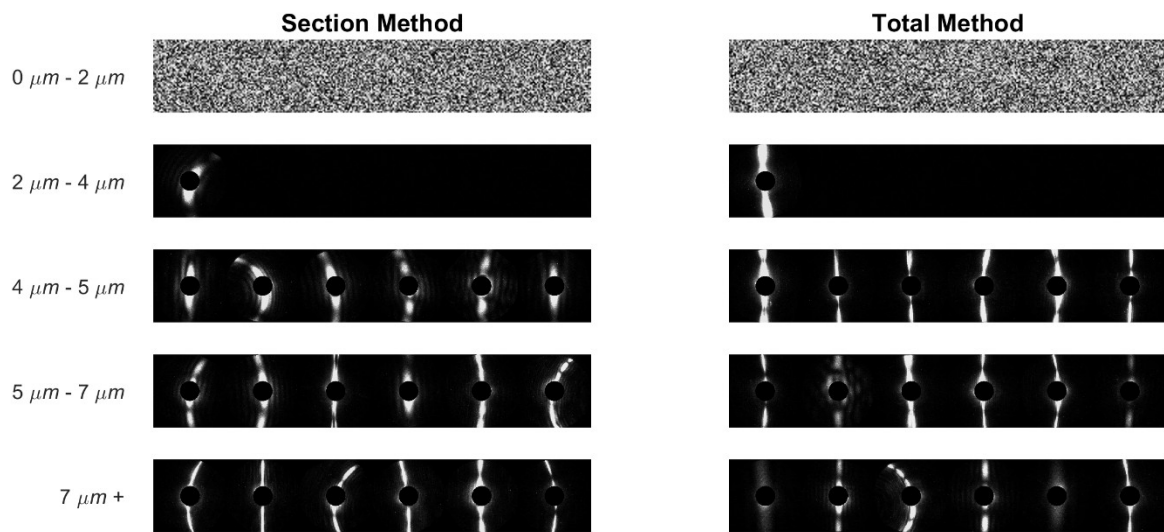


Figure 5.46: Scattering image examples from different length ranges measured using the minimum for the section method (left) and the total method (right). No data was found for the $0\ \mu\text{m} - 2\ \mu\text{m}$ category and only one example each for the $2\ \mu\text{m} - 4\ \mu\text{m}$ category.

A result of the improved signal to noise ratio is the lack of smaller length measurements and not much difference in trend prior to the optimisation.

5.4.3.4 Statistical Analyses

The size distributions for the results seem to be log-normally distributed, resulting in a peak at low size values ($\sim 10\ \mu\text{m}$ for length and $\sim 1.4\ \mu\text{m}$ for diameter) and a long tail towards the higher values. As the distributions are not normal, only non-parametric tests can be performed, i.e., analyses that don't assume the distribution of the data. An assumption of normally distributed data for the analysis of the results of this section would not give a reliable metric into how

similar the distributions of the scattering are to those of the micrograph data. Unfortunately, non-parametric tests are less reliable but more appropriate for this evaluation.

The Mann-Whitney-Willcoxon (or Willcoxon Rank Sum, Mann-Whitney U, etc.) test is a non-parametric test to compare two distributions, evaluating the null hypothesis that the two distributions are from the same population. This is achieved by ranking the observations of the combined datasets and analysing the sum of the ranks for each set. This test was conducted for each dataset of this section and the results are summarised in Table 5.1.

Measurement	Method	P-Value	Hyp. Rejection
Diameter	Section	6.45E-11	TRUE
Diameter	Total	3.34E-36	TRUE
Length	Section	2.61E-119	TRUE
Length	Total	3.90E-140	TRUE

Table 5.1: Mann-Whitney U test results summary for both diameter and length measurements using both the section and total methods compared with the micrograph size distributions.

Unfortunately, for each comparison the null hypothesis that the distributions are taken from the same population are rejected. The P-Values for each show a very small value and represent the probability of the difference in the distributions is found by chance, i.e., the small P-Values in Table 5.1 show that the null hypothesis is extremely unlikely and that the alternative hypothesis of the distributions not being from the same population is more likely.

Alternatively, a comparison of the cumulative distribution functions of the measured sizes can be made using the Two-Sample Kolmogorov–Smirnov test, another viable, non-parametric evaluation. The cumulative distribution functions of the results from this section are shown in Figure 5.47 for both the diameter (left) and length (right) using the section (orange) and total (purple) methods, compared against the micrograph (blue) results. This test evaluates the differences between the scattering (total and section) cumulative distribution function and the microscopy cumulative distribution function for the different sizes found.

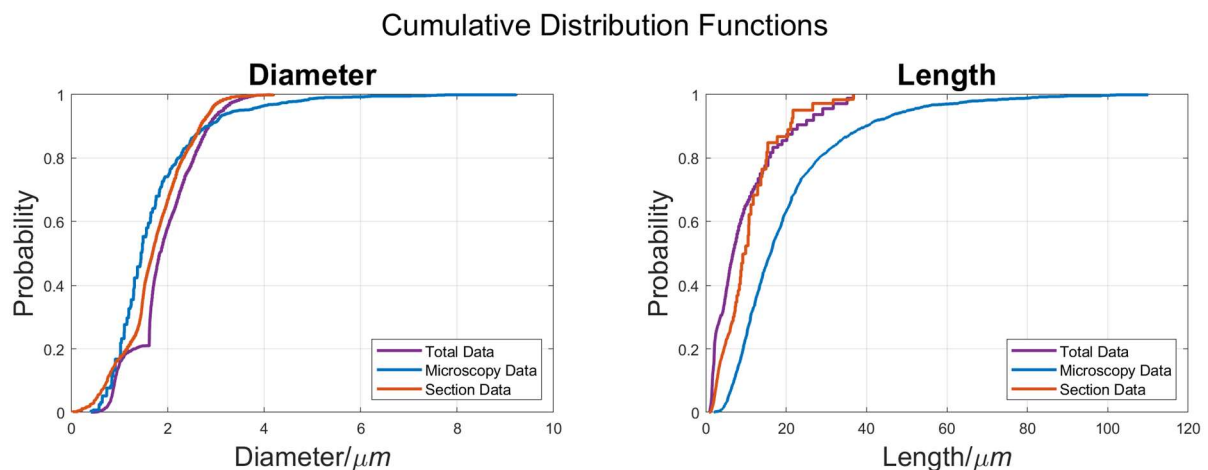


Figure 5.47: Cumulative distribution functions of the diameter (left) and length (right) results for the total (purple) and section (orange) measured scattering data, alongside the micrograph (blue) cumulative distribution functions.

What the cumulative distribution functions of Figure 5.47 show is an under-sizing of the length measurements and an over-sizing of the diameters for most cases. The kink found at $\sim 1.5 \mu\text{m}$ of the diameter plot of Figure 5.47 (left) is the result of the transition between the gradient and

minimum measurements and is reflected in the distributions shown in Figure 5.45. The results of the Two-Sample Kolmogorov-Smirnov tests are summarised in Table 5.2.

Measurement	Method	P-Value	Hyp. Rejection
Diameter	Section	9.35E-29	TRUE
Diameter	Total	1.15E-94	TRUE
Length	Section	1.55E-98	TRUE
Length	Total	3.66E-122	TRUE

Table 5.2: Two-Sample Kolmogorov-Smirnov test results summary for both diameter and length cumulative distribution functions using both the section and total methods compared with the micrograph cumulative distribution function.

Similar to the results of the Mann-Whitney-Willcoxon test, the P-Values of each of the Kolmogorov-Smirnov tests were extremely low. Again, rejecting the null hypothesis, that is the compared datasets are from the same, continuous distribution.

What was found from both of these analyses is that the comparisons between the size distributions of the micrograph data and those taken from the scattering data were not statistically significant. However, many other factors also need to be considered, such as the reliability of the tests, as previously mentioned, and possible biases in the data that may be a result of the settings used for the instrument.

5.5 Discussion

Initially, the overall diameter results showed a poor match between the different distributions. A mild improvement was found in the representation of the data after optimising the bin widths of the histograms but still showed a lack of observations between 1 μm and 1.5 μm when compared to the micrograph data. When separating the diameter measurements of the different measurement methods and the micrograph data at a value of 1.62 μm , a flaw in the gradient measurement method was discovered, showing a slight shift in the scattering data to a smaller diameter. The diameter measurements using the minimum, however, showed a reasonably good match to the corresponding micrograph data for the larger diameter sizes. Solving this under-sizing issue from the gradient measurements would improve the overall diameter distribution comparisons. Additionally, when considering the results shown for the modelled data experiment in Chapter 4, the gradient measurements showed a reliable outcome up to around 1 μm in diameter. After this point the results became less uniform and the measurements using the minimum did not begin until around 1.3 μm – 1.5 μm , coinciding with the dip in the diameter distribution results.

Prior to the alterations of the algorithm and the optimisation of the bin widths at the end of Section 5.4.3.3, the length distributions showed almost no match between the scattering and micrograph data. This was surprising due to the results of the modelled data found in Chapter 4 and spurred an investigation into the measurements of a few example scattering patterns. The sizes measured from the PPD2 scattering images were used to model the scattering using ADDA to investigate how well the measurements matched. A reasonable approximation of the scattering was made by ADDA for the examples used, however, issues were found with the length measurements using the minimum. After improving the signal to noise ratio and optimising the histogram bin widths the distributions showed a vastly improved match with a median value much closer to that of the micrograph result. The lack of observations beyond $\sim 36 \mu\text{m}$ (see Figure 5.43) is due to the reference data becoming non-monotonic around that

point (see Figure 5.18) and so unused. This increase in the signal to noise ratio would render the FWHM measurements redundant and so the unaltered data was retained for these and unfortunately there was no improvement in matching the micrograph distribution, even after the bin width optimisation.

As to the differences found using either the section or total method for measuring the scattering data, the section method seemed to perform better. Slight improvements were found for all measurement techniques when using the section method, this was anticipated due to the under-sizing using the total method caused by orientation (i.e., bright band curvature; see Section 5.4.1.2 and Chapter 4). However, what was not anticipated is a similar trend found in the length measurements using the minimum; further investigation into the dependence of length measurement using the minimum and orientation is required as it was overlooked in Chapter 4.

Additionally, a sampling bias may have also been a cause into the differences in the distributions. Smaller fibres would be harder to locate and measure in the micrographical analysis. Larger particles that scatter much more light than the smaller ones may have caused the PPD2 software to dismiss the scattering as a glitch. Moreover, smaller fibres may have also been dismissed from not reaching the trigger threshold.

Visually, the distribution comparisons looked reasonably good and secured confidence in that these measurement systems would be a reliable way in which fibres could be measured. Unfortunately, the statistical analyses of those comparisons all rejected the hypothesis that they were from the same distribution. The sample sizes for the micrograph measurements were only 200 per fibre sample⁵⁴, due to time restrictions, and the sample sizes of the scattering data were, in some cases, dramatically reduced after failing to meet the criteria outlined in Section 5.3.3.2. The sample sizes may have affected the results, however, as previously stated; the non-parametric tests required for these analyses are much less reliable than parametric tests.

5.6 Conclusion

Overall, the comparisons between the scattering and micrograph size distributions were encouraging, however, a better statistical comparison of the population distributions were expected due to the results of Chapter 4. The diameter distribution comparisons showed a much better match than those of the length, nonetheless, both require improvement and more rigorous testing. The gap in the diameter distributions, that were attributed to the transition between the two diameter measuring methods, could be compensated for extending the angle in which the minimum can be measured. This could potentially bridge this lack of data between 1 μm and 1.5 μm diameters. A vast improvement in the shape of the distributions was found for the length measurements using the minimum compared with those using the FWHM after increasing the signal to noise ratio and the optimisation of the bin widths. Unfortunately, this may be a coincidence as the examples of the categorised scattering images displayed no obvious correlation to the other scattering images within that category. Additionally, no improvement was made after optimisation and resulted in fewer short fibres being measured. It is also worth reiterating that the ADDA-simulated data used as a reference was made using the light scattering from perfect cylinders. In reality, this may not be the case; the micrograph

⁵⁴ 1200 diameter and length measurements in total.

examples shown in Section 5.2.2 and the filter micrograph example shown in Section 5.4.2 display many fibres that deviate from being a perfect cylinder.

Using the minima to measure the diameter and length of a fibre would be a more rigorous method, as these locations will not change depending on the level of gain, or exposure, or the power of the incident light. The FWHM measurements become useless if the data is saturated as the example scattering shown in Section 5.4.3.3 demonstrated. A repeat of this experiment would prove insightful if any saturated images are removed before any of the image manipulation began and include data sets using different settings of PPD2 to account for smaller and larger aerosol. Additionally, the data was only deemed saturated by analysing part of the image, and mostly focused on the length measurements; if saturation is present for the gradient measurements, the gradient would be measured to be higher and therefore a smaller diameter, explaining the shift noticed in Figure 5.37.

An increase in the sample sizes for all measurements could result in an improvement in the statistical comparisons between the measurements made from the scattering data and that measured from the micrographs. For the micrograph data, an automated measurement of the fibres could be made if an alternative filter collection system were to be used. As described in Chapter 1, a system following the WHO guidelines on fibre counting would result in the filters being transparent and so a greater sample size could be recovered through automated measurements. As for the scattering data, a series of aerosolisations could be made for each sample at different camera gain settings. This would compensate for the oversaturation of the larger fibres that scatter too much light, and the underexposure of the smaller fibres that produce less detailed scattering images or fail to reach the trigger threshold. Alternatively, as the PPD2 camera is triggered using the scattering data collected from a PMT, a particle size may be approximated using the trigger data and an adjustment in the camera settings could be altered prior to exposure.

The statistical analyses conducted in this chapter were thought to be a useful exercise in the evaluation of the distribution comparisons. Non-parametric tests were necessary due to the distributions having an unknown shape, i.e., non-normal. It is acknowledged that the constraints of non-parametric tests are much looser than the parametric ones and so it is difficult to interpret the extremely low P-values, especially when the visual comparison of the datasets were encouraging and showed a reasonable correlation between distributions. Even though the interpretation of these test values are unclear, they can (and have been) used to check improvements in the measurement algorithm.

Additionally, neural networks and machine learning algorithms were considered for data analysis but were quickly dismissed. Differentiation between particle type from their scattering patterns can be achieved and work well, as demonstrated by P. Kaye et al. (1997). Training data would be required from the light scattered from fibres of a known size (and possibly other properties) to train the algorithm to identify what scattering patterns correspond to what fibres. The idea was rejected due to the lack of known inputs; to tell the algorithm how to measure the fibre from the scattering, the fibre size must be *a priori* knowledge.

The investigation conducted throughout this chapter has highlighted several possible improvements that could be implemented in future experiments; filter collection techniques, better fibre orientation control, varied or adaptive setting changes of the instrumentation. These would allow for a faster analysis of the data and so a greater sample size could be used. Alternatively, single, pre-measured fibres could be selected and dropped into PPD2 for a direct

comparison of fibre morphology and scattering data. Nonetheless, even without these improvements, the results have demonstrated a reasonable match to the microscopy data. With what has been demonstrated hitherto, shows that the forward scattering of fibres can be used to determine the fibre length and diameter within a reasonable estimate. The exact measurements of each fibre may not be found without much more rigorous experimentation. However, a reasonable estimate of the fibre aspect ratio can be found and subsequently the respirable fraction of the fibrous aerosol. There are several caveats to this statement that have been discussed; however, methods of their possible amelioration have also been included – e.g. using flow alignment to improve orientation.

6 Conclusions and Future Work

*“If after every tempest comes such calms,
May the winds blow till they have waken’d death”
-William Shakespear, Othello, 1603*

6.1 Project Conclusions

6.1.1 Strengths

The Monte Carlo-based testing of the measurement systems, explained in Chapter 4, showed very promising results. The larger outliers seemed to be caused by peculiarities in the algorithm of the measurement which requires further investigation and optimisation. The smaller outliers were the result of a low imaginary refractive index and could be potentially compensated for if the material of the fibres being monitored are known prior to any analysis.

The subsequent experimental investigation (Chapter 5) produced results which were poorer than had been hoped, perhaps not surprising given the greater complexity of real-world data. However, following a good deal of work to optimise the results, the diameter and length measurement distributions are, visually, reasonably well correlated with the micrograph measurements. Some, at least, of the dissimilarities were explained and better results might be possible with further investigation.

Notwithstanding, the results still demonstrate that measurement of the diameter and length of the individual fibres is robust enough that it should be possible to characterise individual fibres as respirable or not under the WHO definition with reasonable confidence, albeit with larger error-bars than one would like. It is clear however that, with the technique as it currently stands, morphological measurements are probably not as precise as current microscopy analysis.

At the very least though, a reasonably accurate estimate of the fraction of respirable fibres in a measured population should be possible with this analytical method. Population studies should be more robust assuming measurement errors are random.

Regardless of the caveats, there is currently no other technique for real-time assessment of single fibre morphology.

6.1.2 Limitations

Results shown in Chapter 5 for the diameters using the gradient measurement showed a shift to a smaller diameter and the length measurements using the FWHM of the scattering gave much worse results than the length measurements using the first angular minimum. Consideration of the intensity of the scattering images, captured by PPD2, were not made. The modelled scattering images are generated with the intensities normalised by the model. Any measurement made from the scattering image that may depend on the intensity, such as the gradient or FWHM, may be wrong depending on the instrument set-up. The settings of PPD2, such as exposure time and camera gain, coupled with the particle itself, will affect the intensity of the scattering image causing underexposure or saturation. Normalising this may then lead to incorrect measurements from saturation or noise amplification.

The noise of the captured scattering image is also a limiting factor, unrepresented in the modelled data. Compensating for the noise found in the images from PPD2 was attempted. Filtering or smoothing the signals decreased the chance of false measurements of any minimum point found due to noise, however, the level of filtering or smoothing required may remove important features, leading to wrong or no measurement at all. Additionally, setting a threshold of the prominence of the minimum points found has the same outcome. Combinations of the filtering and prominence thresholding were explored but not as extensively analysed as the other optimisation processes.

With regard to the experimental investigation there are various difficulties. As mentioned in Chapters 1 and 2, the generation of a fibrous aerosol of identical morphologies is difficult to achieve. Consequently, it was only possible to work with poly-dispersed samples preventing a direct fibre-fibre comparison between the scattering and micrograph measurements.

The population distributions of the length measurements from the micrograph analysis, shown in Chapter 5, were truncated to include up to 30 μm in length, with single histogram bin for lengths greater than 30 μm . Some fibres were found to be as long as 100 μm , which no doubt contributed to the significant differences in the median values obtained for the sample from the light scattering patterns, given that the reference data was limited to a length of $\sim 36 \mu\text{m}$. And, of course, the shape of the distributions would be affected. Due to time restrictions, only 200 measurements for each of the six samples were made and may not be as representative of the population distribution compared with the diameter measurements, due to this large range of possible lengths. Finally, the filter collection method used for the micrograph analysis resulted in an unwanted textured background, obscuring some of the fibres and making them more difficult to measure.

It is worth reiterating the different problems found with accounting for longer fibres. There is no stated upper length limit for respirable fibres within the WHO or NIOSH regulations, nonetheless, a rule of thumb has been suggested for 15 μm . However, recalling the discussion of the aerodynamic properties of fibres in Chapter 1, and the evidence from autopsy (reporting a 400 μm found in the patient's lung), it is clear that longer fibres can and have been found deposited within the human lung. Although this may not be common, it was felt, nevertheless, to be an important phenomenon and hence, the attempt to include an extended length range in the studies presented here. This proved to be more difficult than anticipated since the reference data for the length measurements using the minimum had to be truncated due to the non-monotonic behaviour with any measurement made for a fibre beyond this limit being found through extrapolation of the available data. This erratic behaviour is believed to be a weakness with the minimum-finding algorithm, due to the erratic shape of Figure 5.18 (right), and may be alleviated with the reproduction of said data with higher-resolution images. Due to the complex nature of this problem, and many others within this research, time restrictions prevented additional investigations that arrived from the evaluation of the results.

It is perhaps not surprising therefore that the two-sample hypothesis tests carried out were negative in all cases. However, they might prove useful for assessing attempts at improving the performance of the scattering analysis discussed below.

6.1.3 Future work

Reflecting on the overall limitations of this project, many ideas for improvement can be identified. To start, a simple improvement would be to repeat the aerosolisation experiment of

Chapter 5, with varied exposure time and camera gain settings for PPD2. Allowing more light to be captured by the PPD2 camera would create a greater number of saturated images for the larger particles, as they scatter more light. However, more detail of the smaller particles would be found. Conversely, allowing less light to be captured would reduce the number of saturated images, for a better analysis of the larger fibres. A comparison of how the population distributions may change with different exposure and camera settings would provide insights into how much the measurement system relies on the settings of the instrument. Furthermore, as the measurement results using the minimum points showed an improved comparison of the population distributions, a greater scattering angle could be used for a more accurate measurement of the fibre diameters between $\sim 1\ \mu\text{m}$ and $\sim 1.5\ \mu\text{m}$. There are techniques for applying logarithmic gain to signal data to boost low level signals while minimising saturation at the high end. This could aid both the detection and accuracy of measurements of pattern minima in general and measurement of smaller fibres.

Regarding the noise found in the scattering images and the filtering or thresholding required by the measurement system, both alterations to the instrument and further optimisation of algorithm should provide an improvement. From an extensive optimisation process of the noise filtering, a compromise could be found for the filtering and thresholding process. However, this would require an iterative analysis of individual scattering images by hand, a long and tedious process. Alternatively, optimisation of the PPD2 settings or a higher resolution camera may produce a less noisy image.

Due to the lack of direct comparisons of an individual fibre and the scattered light it produces, additional experiments could be conducted for a more robust analysis of the measurement system. The micro-machined particles, mentioned in Chapter 1, would make a reliable source of identical fibrous samples if the difficulties with aerosolisation can be overcome. Alternatively, by pre-measuring individual fibres and aerosolising them in a clean environment, individually through PPD2, a direct comparison between the fibre and the scattered light could be made. However, this would also be quite a difficult and time-consuming task due to the size of the fibres and the number of fibres required to make a significant observation but this has been done previously. Additionally, the levitation of individual fibres using an electrodynamic balance (EDB) would allow for the capture of the scattering patterns from the fibre and subsequent deposition of the fibre for analysis via SEM, as explored by Hesse et al. (2002). It is acknowledged, however, that levitating high aspect ratio particles is not trivial.

The comparisons of the population distributions of the length measurements showed poorer results than those of the diameter which, in part, may be attributed to sample size. An increase in the number of measurements from the micrograph analysis may then improve these results but the sample collection method would have to be re-designed to reduce the time required for these measurements. By using mixed cellulose ester filters and using an acetone vapor clearing method, as is regulations of the WHO and explained in Chapter 1, the collected fibres would be easier to see and a possible automated measurement of their length and diameter could be performed.

Some aspects of the fibre properties in relation to the resulting scattering image were investigated in Chapter 4, such as orientation and curvature, but could not be incorporated into the experiment in Chapter 5 due to time restrictions. It was demonstrated that as the orientation changed and the resulting bright band deformed into curve, the usual measurement methods gave increasingly poor results. However, the radius of curvature of the deformed bright band can be measured and most likely be accommodated for. Better still, there are ways to

control the flow such that the fibres have a more constrained alignment. As explained in Chapter 1, the ALERT system aligned ~85% of the fibres within 10° of the flow direction. The brief orientation investigation in Chapter 4 showed for a misalignment of 10°, a difference in the FWHM measurement was ~0.01°, translating to a difference in length of around 0.1 µm and the diameter slightly more. This has not been thoroughly investigated with the latest measurement system and is expected to equate to a larger difference. Nonetheless, flow alignment of the fibres combined with compensation for misaligned fibres, would contribute to a larger set of data for more rigorous testing. Also mentioned in Chapter 4 was light scattering patterns produced by curved fibres, producing a “bowtie” pattern. As the current system of measurement, described in this project, may not be adequate for these fibres, further investigation is required. The ability to detect and measure these fibres may lead to the differentiation of fibre types, as well as their morphological details.

6.2 Instrumentation Design – What Can Be Achieved

The analysis approach considered here may well be a sound basis for providing a good estimate of the respirable fraction of fibres in a sample that correspond to the definition of WHO regulations. This requires a pre-filtering of the data which, for this project, was carried out manually as discussed in Section 5.4.1.2. These unwanted data include noise, non-fibres, curved fibres, and poorly oriented fibres. There are, however, techniques for automating the filtering which would be incorporated into a prototype instrument design. Problems with orientation can be easily improved with flow alignment, as discussed in Section 1.3.4.3 regarding the ALERT system. The noise and some non-fibres may be filtered out using the peak to mean (P2M) measurements of the rotational mean (see Appendix 7.4), the horizontal section (for length measurement – see Section 4.3.1.4), or a combination of the two. Figure 6.1 shows randomly selected scattering data from gypsum that has been categorised using these techniques; rotational, sectional, and combination results in the columns from left to right. A clear definition of noise is found for lower P2M values, however, there is still some ambiguity in categorisation concerning some of the intermediates. When considering P2M values greater than those of the third row of Figure 6.1, anywhere between 15% and 30% of the data is retained.

Peak-to-Mean Categorisation Examples

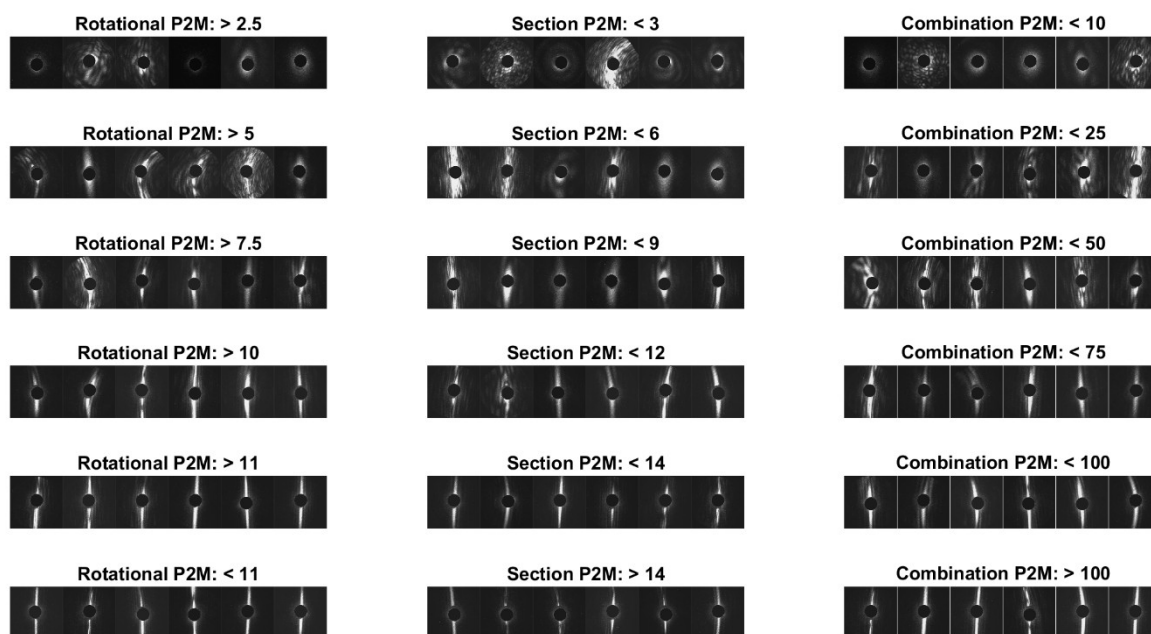


Figure 6.1: Scattering examples from gypsum fibres, captured using PPD2, categorised into different peak to mean (P2M) values. The columns show the rotational mean P2M, the sectional mean P2M, and a combination from left to right respectively.

Realistically, what has been found within this project has not been tested rigorously enough for accurate size measurements of individual fibrous aerosol. Any instrument constructed using this research in its current state would not provide a drop-in replacement for standard laboratory methods, notwithstanding the high error margins associated with these standard techniques. Nonetheless, a “smoke detector”-like warning system could measure the respirable fraction of airborne fibres to a reasonable level of reliability. If the concentration level is found to meet or exceeded a given threshold, subsequent action could be taken, i.e., quarantine until more regulated testing can confirm the presence of respirable fibres. This would greatly benefit tradespeople and the general public by minimising exposure.

Verma et al. (2004) analysed MMMF fibre samples, collected using WHO guidelines, of various construction workers to assess the fibre type and level of exposure they are regularly subjected to. The list of tradespeople included painters, cement masons, labourers, insulators, carpenters, boiler makers, bricklayers, roofers, water-proofers, and floor-layers. Their work also includes a list of activities, such as cutting and handling, that these tradespeople undertook, and included overall values of respirable fibre concentrations found using both personal and area samplers. The concentrations were reported to be below the regulations-specified detection limit, nonetheless, this demonstrates the plethora of exposure risks to anyone who directly works with MMMFs. Additionally, Noonan (2017) investigates occupational exposure of asbestos and how workers can be vectors that inadvertently become sources of exposure, i.e., para-occupational exposure, highlighting the risks for people associated with these workers.

Considering non-occupational exposure, Allen et al. (2023) review several articles that investigate public buildings and respirable MMVFs found within. The types of buildings included homes, schools, and offices and again, most of the investigations reported fibre concentrations below the detection limit. A study was conducted by Schneider et al. (1996) that used personal

samplers to monitor the respirable fibre exposure of groups of different people around Europe. These groups were taxi-drivers, school children, office workers, and retirees and monitored the exposure to organic, inorganic, and gypsum fibres, finding that school children had the largest fibre concentration for each fibre type.

Using the measurement algorithm described within this research, including a rudimentary filter for unsuitable data, the experiment described in Chapter 5 could be repeated with the improvements discussed. Filter collection of the aerosolised fibre samples using the WHO regulation IOM sampler alongside the light scattering measurements would provide a more reliable evaluation of the algorithm. A bench-top prototype of an instrument could be made and used in parallel with the PPD2. If the same algorithm is used on both sets of data, a comparison of the size distributions would confirm the applicability of the algorithm in different optical systems. An initial aim is to develop an affordable warning system with wide applicability in industry and beyond.

Bibliography

- Alleman, J. E., & Mossman, B. T. (1997). Asbestos Revisited. *Scientific American*, 277(1), 70–75. <https://doi.org/10.2307/24995833>
- Allen, L. H., Suder Egnot, N., Allen, H., Chan, K., & Marsh, G. (2023). Exposure to MMVF in residential and commercial buildings: A literature review and quantitative synthesis. In *Toxicology and Industrial Health* (Vol. 39, Number 9, pp. 528–536). SAGE Publications Ltd. <https://doi.org/10.1177/07482337231187092>
- Ambrosio, L. A., de Sarro, J. O., & Gouesbet, G. (2024). An approach for a polychromatic generalized Lorenz–Mie theory. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 312. <https://doi.org/10.1016/j.jqsrt.2023.108824>
- Andersson, M., Wittgren, B., & Wahlund, K.-G. (2003). *Accuracy in Multiangle Light Scattering Measurements for Molar Mass and Radius Estimations. Model Calculations and Experiments*. <https://doi.org/10.1021/AC030128>
- Aptowicz, K. B., Pinnick, R. G., Hill, S. C., Pan, Y. L., & Chang, R. K. (2006). Optical scattering patterns from single urban aerosol particles at Adelphi, Maryland, USA: A classification relating to particle morphologies. *Journal of Geophysical Research Atmospheres*, 111(12). <https://doi.org/10.1029/2005JD006774>
- Asadova, N., Achouri, K., Arjas, K., Auguié, B., Aydin, R., Baron, A., Beutel, D., Bodermann, B., Boussaoud, K., Burger, S., Choi, M., Czajkowski, K. M., Evlyukhin, A. B., Fazel-Najafabadi, A., Fernandez-Corbaton, I., Garg, P., Globosits, D., Hohenester, U., Kim, H., ... Zouros, G. P. (2024). *T-matrix representation of optical scattering response: Suggestion for a data format*. <http://arxiv.org/abs/2408.10727>
- Asbestos.com. (2025). *The Mesothelioma Center: Support for Cancer Patients & Families*. <https://www.asbestos.com/>
- Asthaigiri, D., Paliwal, A., Abras, D., Lenhoff, A. M., & Paulaitis, M. E. (2005). A consistent experimental and modeling approach to light-scattering studies of protein-protein interactions in solution. *Biophysical Journal*, 88(5), 3300–3309. <https://doi.org/10.1529/biophysj.104.058859>
- Ballington, H., & Hesse, E. (2024). A light scattering model for large particles with surface roughness. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 323. <https://doi.org/10.1016/j.jqsrt.2024.109054>
- Bänninger, D., & Flühler, H. (2004). Modeling light scattering at soil surfaces. *IEEE Transactions on Geoscience and Remote Sensing*, 42(7), 1462–1471. <https://doi.org/10.1109/TGRS.2004.828190>
- Baran, A. J., Hesse, E., & Sourdeval, O. (2017). The applicability of physical optics in the millimetre and sub-millimetre spectral region. Part I: The ray tracing with diffraction on facets method. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 190, 13–25. <https://doi.org/10.1016/j.jqsrt.2016.12.030>
- Baron, P. A. (1994). Direct-reading Instruments for Aerosols. *Analyst*, 119.

- Bell, B. W., & Bickel, W. S. (1981). *Single fiber light scattering matrix: an experimental determination*.
- Bohren, C. F., & Huffman, D. R. (1998). *Absorption and Scattering of Light by Small Particles*. John Wiley & Sons.
- Breyse, P. N., Cherrie, J. W., Leest, J. P. S. J., & Brown, P. (1994). COMPARISON OF NIOSH 7400 “B” RULES AND WHO REFERENCE METHODS FOR THE EVALUATION OF AIRBORNE MAN-MADE MINERAL FIBRES*. In *Hya* (Vol. 38).
https://academic.oup.com/annweh/article/38/inhaled_particles_VII/527/209217
- Bronkema, D. (1988). Asbestos: The Birth of a Regulation. *EPA Journal*, 14.
<https://heinonline.org/HOL/Page?handle=hein.journals/epajrnl14&id=54&div=&collection=>
- Bulot, F. M. J., Russell, H. S., Rezaei, M., Johnson, M. S., Ossont, S. J. J., Morris, A. K. R., Basford, P. J., Easton, N. H. C., Foster, G. L., Loxham, M., & Cox, S. J. (2020). Laboratory Comparison of Low-Cost Particulate Matter Sensors to Measure Transient Events of Pollution. *Sensors* 2020, Vol. 20, Page 2219, 20(8), 2219. <https://doi.org/10.3390/S20082219>
- Cauda, E., Dolan, E., Cecala, A., Louk, K., Yekich, M., Chubb, L., & Lingenfelter, A. (2022). Benefits and limitations of field-based monitoring approaches for respirable dust and crystalline silica applied in a sandstone quarry. *Journal of Occupational and Environmental Hygiene*, 19(12), 730–741. <https://doi.org/10.1080/15459624.2022.2132257>
- Chaumet, P. C. (2022). The Discrete Dipole Approximation: A Review. In *Mathematics* (Vol. 10, Number 17). Multidisciplinary Digital Publishing Institute (MDPI).
<https://doi.org/10.3390/math10173049>
- Chaumet, P. C., Rahmani, A., & Nieto-Vesperinas, M. (2002). Optical Trapping and Manipulation of Nano-objects with an Apertureless Probe. *Physical Review Letters*, 88(12), 4.
<https://doi.org/10.1103/PHYSREVLETT.88.123601>
- Chawla, K. K. (2001). Glass Fibers. *Encyclopedia of Materials: Science and Technology*, 3541–3545. <https://doi.org/10.1016/B0-08-043152-6/00630-6>
- Cherrie, J., Krantz, S., Schneider, T., Ohberg, I., & Kamstrup, O. (1987). AN EXPERIMENTAL SIMULATION OF AN EARLY ROCK WOOL/SLAG WOOL PRODUCTION PROCESS. In *Ann. occup Hyg* (Vol. 31). <https://academic.oup.com/annweh/article/31/4B/583/161929>
- Clarke, A. J. M., Hesse, E., Ulanowski, Z., & Kaye, P. H. (2006). A 3D implementation of ray tracing combined with diffraction on facets: Verification and a potential application. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 100(1–3), 103–114.
<https://doi.org/10.1016/j.jqsrt.2005.11.028>
- Clouter, A., Houghton, C. E., Hibbs, L. R., & Hoskins, J. A. (1998). EFFECT OF INHALATION OF LOW DOSES OF CROCIDOLITE AND FIBROUS GYPSUM ON THE GLUTATHIONE CONCENTRATION AND g-GLUTAMYL TRANSPEPTIDASE ACTIVITY IN MACROPHAGES AND BRONCHOALVEOLAR LAVAGE FLUID. In *Inhalation Toxicology* (Vol. 10).
- Cooke, W. E. (1924). *FIBROSIS OF THE LUNGS DUE TO THE INHALATION OF ASBESTOS DUST*.

- Crawford, N. P., Kello, D., & Jarvisalo, J. O. (1987). MONITORING AND EVALUATING MAN-MADE MINERAL FIBRES: WORK OF A WHO/EURO REFERENCE SCHEME. In *Ann occup Hyg* (Vol. 31, Number 4B). <https://academic.oup.com/annweh/article/31/4B/557/161895>
- Di Giuseppe, D. (2020). Characterization of fibrous mordenite: A first step for the evaluation of its potential toxicity. *Crystals*, 10(9), 1–15. <https://doi.org/10.3390/cryst10090769>
- Doicu, A., Wriedt, T., & Eremin, Y. (2019). *Light Scattering by Systems of Particles: Null-Field Method with Discrete Sources: Theory and Programs*. Scholars Portal.
- Doicu, & Adrian. (2000). Acoustic and Electromagnetic Scattering Analysis Using Discrete Sources. *Aesa*, ix–xi. <https://doi.org/10.1016/B978-012219740-6/50000-9>
- Donaldson, K., & Tran, C. L. (2004). An introduction to the short-term toxicology of respirable industrial fibres. *Mutation Research - Fundamental and Molecular Mechanisms of Mutagenesis*, 553(1–2), 5–9. <https://doi.org/10.1016/j.mrfmmm.2004.06.011>
- Draine, B. T. (1988). The discrete-dipole approximation and its application to interstellar graphite grains. *The Astrophysical Journal*. <https://adsabs.harvard.edu/full/1988ApJ...333..848D>
- Elovskaja, L., & Kovalevsky, E. (2002). The Inadequacy of Describing Fibres by Counting Techniques. *Ann. Occup. Hyg*, 46, 115–117. <https://doi.org/10.1093/annhyg/mef646>
- Eremina, E., & Wriedt, T. (2003). *Review of light scattering by fiber particles with a high aspect ratio*.
- Ermolaev, G. A., Tsapenko, A. P., Volkov, V. S., Anisimov, A. S., Gladush, Y. G., & Nasibulin, A. G. (2020). Express determination of thickness and dielectric function of single-walled carbon nanotube films. *Applied Physics Letters*, 116(23). <https://doi.org/10.1063/5.0012933>
- Ervik, T. K., Hammer, S. E., Skaugset, N. P., & Graff, P. (2023). Measurements of airborne asbestos fibres during refurbishing. *Annals of Work Exposures and Health*, 67(8), 952–964. <https://doi.org/10.1093/annweh/wxad041>
- Farone, W. A., & Kerker, M. (1966). *Light Scattering from Long Submicron Glass Cylinders at Normal Incidence**.
- Fokkema, D. R. (1996). *ENHANCED IMPLEMENTATION OF BICGSTAB FOR SOLVING LINEAR SYSTEMS OF EQUATIONS*.
- Fukushima, S., Kasai, T., Senoh, H., Umeda, Y., Mine, T., Sasaki, T., Kondo, H., Matsumoto, M., & Aiso, S. (2023). Contribution of toxicological pathology to occupational health: lung carcinogenicity of fibrous and particulate substances in rats. In *Journal of Toxicologic Pathology* (Vol. 36, Number 2, pp. 69–83). Japanese Society of Toxicologic Pathology. <https://doi.org/10.1293/tox.2022-0086>
- Furuya, S., Chimed-Ochir, O., Takahashi, K., David, A., & Takala, J. (2018). Global asbestos disaster. *International Journal of Environmental Research and Public Health*, 15(5). <https://doi.org/10.3390/ijerph15051000>
- Gilev, K., Eremina, E., Yurkin, M., & Malstev, V. (2010). Comparison of the discrete dipole approximation and the discrete source method for simulation of light scattering by red blood cells. *Optics Express*. <https://opg.optica.org/abstract.cfm?uri=oe-18-6-5681>

- Görner, P., Wrobel, R., Mička, V., Škoda, V., Denis, J., & Fabriès, J. (2001). Study of Fifteen Respirable Aerosol Samplers Used in Occupational Hygiene. In *Ann. occup. Hyg* (Vol. 45, Number 1). <https://academic.oup.com/annweh/article/45/1/43/172162>
- Gouesbet, G. (2008). Generalized Lorenz-Mie theories, the third decade: A perspective. *Journal of Quantitative Spectroscopy & Radiative Transfer*, 110, 1223–1238. <https://doi.org/10.1016/j.jqsrt.2009.01.020>
- Gouesbet, G., Mees, L., Gréhan, G., & Ren, K. F. (1999). Structure of generalized Lorenz-Mie theory for elliptical infinite cylinders. *Particle and Particle Systems Characterization*, 16(1), 3–10. [https://doi.org/10.1002/\(SICI\)1521-4117\(199905\)16:1<3::AID-PPSC3>3.0.CO;2-7](https://doi.org/10.1002/(SICI)1521-4117(199905)16:1<3::AID-PPSC3>3.0.CO;2-7)
- Grzebyk, M., Kauffer, E., & Fréville, L. (2005). Proposal to adapt the workplace analysis scheme for proficiency (WASP) programme to fibre counting tests. *Annals of Occupational Hygiene*, 49(4), 325–334. <https://doi.org/10.1093/annhyg/mei017>
- Gupta, S. S., Singh, K. P., Gupta, S., Dusinska, M., & Rahman, Q. (2022). Do Carbon Nanotubes and Asbestos Fibers Exhibit Common Toxicity Mechanisms? In *Nanomaterials* (Vol. 12, Number 10). MDPI. <https://doi.org/10.3390/nano12101708>
- Hagan, D. H., & Kroll, J. H. (2020). Assessing the accuracy of low-cost optical particle sensors using a physics-based approach. *Atmospheric Measurement Techniques*, 13(11), 6343–6355. <https://doi.org/10.5194/AMT-13-6343-2020>
- Harper, M., & Bartolucci, A. (2003). Preparation and examination of proposed consensus reference standards for fiber-counting. *American Industrial Hygiene Association Journal*, 64(2), 283–287. <https://doi.org/10.1080/15428110308984819>
- Hasheminasab, F., Aminossadati, S. M., Bagherpour, R., & Amanzadeh, M. (2017). Fibre-Optic Based Sensors for Dust Monitoring. *Proceedings - 2017 2nd International Conference of Fibre-Optic and Photonic Sensors for Industrial and Safety Applications, OFSIS 2017*, 33–38. <https://doi.org/10.1109/OFSIS.2017.22>
- Hecht, E. (2017). *Optics* (8th ed.). Pearson Education, Incorporated.
- Hellawell, E. E., & Hughes, S. J. (2021). Asbestos contamination on brownfield development sites in the UK. *Environmental Research*, 198. <https://doi.org/10.1016/j.envres.2020.110480>
- Hesse, E. (2008). Modelling diffraction during ray tracing using the concept of energy flow lines. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 109(8), 1374–1383. <https://doi.org/10.1016/j.jqsrt.2007.11.002>
- Hesse, E., Mc Call, D. S., Ulanowski, Z., Stopford, C., & Kaye, P. H. (2009). Application of RTDF to particles with curved surfaces. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 110(14–16), 1599–1603. <https://doi.org/10.1016/j.jqsrt.2009.01.011>
- Hesse, E., & Ulanowski, Z. (2003). Scattering from long prisms computed using ray tracing combined with diffraction on facets. In *Journal of Quantitative Spectroscopy & Radiative Transfer* (Vol. 79). www.elsevier.com/locate/jqsrt
- Hesse, E., Ulanowski, Z., & Kaye, P. H. (2002). Stability characteristics of cylindrical fibres in an electrodynamic balance designed for single particle investigation. *Journal of Aerosol Science*, 33(1), 149–163. [https://doi.org/10.1016/S0021-8502\(01\)00153-7](https://doi.org/10.1016/S0021-8502(01)00153-7)

- Hirst, E., & Kaye, P. H. (1996). Experimental and theoretical light scattering profiles from spherical and nonspherical particles. *Journal of Geophysical Research Atmospheres*, 101(14), 19231–19235. <https://doi.org/10.1029/95jd02343>
- Hirst, E., Kaye, P. H., Greenaway, R. S., Field, P., & Johnson, D. W. (2001). Discrimination of micrometre-sized ice and super-cooled droplets in mixed-phase cloud. *Atmospheric Environment*, 35(1), 33–47. [https://doi.org/10.1016/S1352-2310\(00\)00377-0](https://doi.org/10.1016/S1352-2310(00)00377-0)
- Hofmann, W. (2011). Modelling inhaled particle deposition in the human lung-A review. In *Journal of Aerosol Science* (Vol. 42, Number 10, pp. 693–724). Elsevier Ltd. <https://doi.org/10.1016/j.jaerosci.2011.05.007>
- Hovenier, J. W. (1994). Structure of a general pure Mueller matrix. *Applied Optics*, Vol. 33, Issue 36, Pp. 8318–8324, 33(36), 8318–8324. <https://doi.org/10.1364/AO.33.008318>
- Iles, P. J., & Shenton-Taylor, T. (1986). COMPARISON OF A FIBROUS AEROSOL MONITOR (FAM) WITH THE MEMBRANE FILTER METHOD FOR MEASURING AIRBORNE ASBESTOS CONCENTRATIONS. In *Ann. occup. Hyg* (Vol. 30, Number 1). <https://academic.oup.com/annweh/article/30/1/77/150676>
- Jianzhong, L., Weifeng, Z., & Zhaosheng, Y. (2004). Numerical research on the orientation distribution of fibers immersed in laminar and turbulent pipe flows. *Journal of Aerosol Science*, 35(1), 63–82. [https://doi.org/10.1016/S0021-8502\(03\)00388-4](https://doi.org/10.1016/S0021-8502(03)00388-4)
- Jones, A. D., Apsley, A., Clark, S., Addison, J., Van Orden, D. R., & Lee, R. J. (2010). Laboratory tests to compare airborne respirable mass and fibre concentrations from soil samples from Libby, Montana. *Indoor and Built Environment*, 19(2), 286–297. <https://doi.org/10.1177/1420326X09349908>
- Jones, A. D., Arroyo, M. C., Grosjean, R., Tylee, B., Miller, B. G., & Brown, P. (2005). A comparison of fibre counting across three European national proficiency testing schemes. *Annals of Occupational Hygiene*, 49(4), 309–324. <https://doi.org/10.1093/annhyg/meh100>
- Kahnert, F. M. (2003). Numerical methods in electromagnetic scattering theory. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 79–80, 775–824. [https://doi.org/10.1016/S0022-4073\(02\)00321-7](https://doi.org/10.1016/S0022-4073(02)00321-7)
- Kauffer, E., Martin, P., Grzebyk, M., Villa, M., & Vigneron, J. C. (2003). Comparison of two direct-reading instruments (FM-7400 and Fibrecheck FC-2) with phase contrast optical microscopy to measure the airborne fibre number concentration. *Annals of Occupational Hygiene*, 47(5), 413–426. <https://doi.org/10.1093/annhyg/meg055>
- Kaye, P. H. (1998). Spatial light-scattering analysis as a means of characterizing and classifying non-spherical particles. *Measurement Science and Technology*, 9, 141–149.
- Kaye, P. H., Hirst, E., Clark, J. M., & Micheli, F. (1992). AIRBORNE PARTICLE SHAPE AND SIZE CLASSIFICATION FROM SPATIAL LIGHT SCATTERING PROFILES. In *J. Aerosol Sci* (Vol. 23, Number 6).
- Kaye, P. H., Hirst, E., Foot, V. E., Clark, J. M., & Baxter, K. L. (2004). A low-cost multichannel aerosol fluorescence sensor for networked deployment. <https://doi.org/10.1117/12.578283>, 5617, 388–398. <https://doi.org/10.1117/12.578283>

- Kaye, P. H., Hirst, E., Greenaway, R. S., Ulanowski, Z., Hesse, E., Demott, P. J., Saunders, C., & Connolly, P. (2008). *Classifying atmospheric ice crystals by spatial light scattering*.
- Kaye, P. H., Micheli, F., Tracey, M. C., Hirst, E., & Gundlach, A. M. (1992). The Production of Precision Silicon Micromachined Non-Spherical Particles for Aerosol Studies. *Journal of Aerosol Science*, 23(1), 201–204.
- Kaye, P. H., Micheli, F., Tracey, M. C., Hirst, E., & Gundlach, A. M. (1992). The Production of Precision Silicon Micromachined Non-Spherical Particles for Aerosol Study. *Journal of Aerosol Science*, 23, S201–S204.
- Kaye, P. H., Stanley, W. R., Hirst, E., Foot, E., Baxter, K. L., & Barrington, S. J. (2005). Optically Based Biological and Chemical Sensing for Defence. In J. C. Carrano, *Director, Sensors and Command* (Vol. 23, Number 10). <http://www.darpa.mil/mto/suvos/>
- Kaye, P., Hirst, E., & Wang-Thomas, Z. (1997). Neural-network-based spatial light-scattering instrument for hazardous airborne fiber detection. *Applied Optics*, Vol. 36, Issue 24, Pp. 6149-6156, 36(24), 6149–6156. <https://doi.org/10.1364/AO.36.006149>
- Kehren, D., Simonow, B., Bäger, D., Dziurawitz, N., Wenzlaff, D., Thim, C., Neuhoﬀ, J., Meyer-Plath, A., & Plitzko, S. (2019). Release of respirable fibrous dust from carbon fibers due to splitting along the fiber axis. *Aerosol and Air Quality Research*, 19(10), 2185–2195. <https://doi.org/10.4209/aaqr.2019.03.0149>
- Kister, G., Wang, L., Ralph, B., & Fernando, G. F. (2003). *Self-sensing E-glass fibres*. www.elsevier.com/locate/optmat
- Kotsis, I., & Balogh, A. (1989). Synthesis of Wollastonite. In *Ceramics International* (Vol. 15).
- Kuroda, A. (2021). Recent progress and perspectives on the mechanisms underlying Asbestos toxicity. In *Genes and Environment* (Vol. 43, Number 1). BioMed Central Ltd. <https://doi.org/10.1186/s41021-021-00215-0>
- Langer, A. M., Mackler, A. D., & Pooley, F. D. (1974). Electron Microscopical Investigation of Asbestos Fibers. In *Environmental Health Perspectives* (Vol. 9).
- Lemasters, G. K., Lockey, J. E., Levin, L. S., McKay, R. T., Rice, C. H., Horvath, E. P., Papes, D. M., Lu, J. W., & Feldman, D. J. (1998). *An Industry-wide Pulmonary Study of Men and Women Manufacturing Refractory Ceramic Fibers* (Vol. 148, Number 9). <https://academic.oup.com/aje/article/148/9/910/125613>
- Li, H., Xiong, Y., & Chen, Y. (2024). Simulation of Complex Meteorological Target Echoes for Airborne Dual-Polarization Weather Radar Based on Invariant Imbedding T -Matrix. *IEEE Transactions on Geoscience and Remote Sensing*, 62. <https://doi.org/10.1109/TGRS.2024.3396087>
- Li, X., Su, X., Wei, L., Zhang, J., Shi, D., & Wang, Z. (2024). Assessing trends and burden of occupational exposure to asbestos in the United States: a comprehensive analysis from 1990 to 2019. *BMC Public Health*, 24(1). <https://doi.org/10.1186/s12889-024-18919-7>
- Lu, L., Wu, X., Chen, L., Liu, L., Li, Y., & Wang, X. (2022). Optical measurement method of non-spherical particle size and concentration based on high-temperature melting technique. *Measurement*, 198, 263–2241. <https://doi.org/10.1016/j.measurement.2022.111375>

- Luyt, A. S., Dramićanin, M. D., Antić, Ž., & Djoković, V. (2009). Morphology, mechanical and thermal properties of composites of polypropylene and nanostructured wollastonite filler. *Polymer Testing*, 28(3), 348–356. <https://doi.org/10.1016/J.POLYMERTESTING.2009.01.010>
- Macke, A., Mueller, J., & Raschke, E. (1996). Single scattering properties of atmospheric ice crystals. *Journal of the Atmospheric Sciences*.
- Madl, A. K., & O'Neill, H. C. (2022). Fiber biodurability and biopersistence: historical toxicological perspective of synthetic vitreous fibers (SVFs), the long fiber paradigm, and implications for advanced materials. In *Critical Reviews in Toxicology* (Vol. 52, Number 10, pp. 811–866). Taylor and Francis Ltd. <https://doi.org/10.1080/10408444.2022.2154636>
- Mahrt, F., Wieder, J., Dietlicher, R., Smith, H. R., Stopford, C., & Kanji, Z. A. (2019). A high-speed particle phase discriminator (PPD-HS) for the classification of airborne particles, as tested in a continuous flow diffusion chamber. *Atmospheric Measurement Techniques*, 12(6), 3183–3208. <https://doi.org/10.5194/AMT-12-3183-2019>
- Markowicz, K. M., & Chyliński, M. T. (2020). Evaluation of Two Low-Cost Optical Particle Counters for the Measurement of Ambient Aerosol Scattering Coefficient and Ångström Exponent. *Sensors* 2020, Vol. 20, Page 2617, 20(9), 2617. <https://doi.org/10.3390/S20092617>
- Maxim, L. D., & McConnell, E. E. (2005). A review of the toxicology and epidemiology of wollastonite. In *Inhalation Toxicology* (Vol. 17, Number 9, pp. 451–466). <https://doi.org/10.1080/08958370591002030>
- Maxim, L. D., & Utell, M. J. (2018). Review of refractory ceramic fiber (RCF) toxicity, epidemiology and occupational exposure. In *Inhalation Toxicology* (Vol. 30, Number 2, pp. 49–71). Taylor and Francis Ltd. <https://doi.org/10.1080/08958378.2018.1448019>
- Meyer-Plath, A., Kehren, D., Große, A., Naumann, R., Hofmann, M., Schneck, T., Ota, A., Hermanutz, F., Dziurawitz, N., Thim, C., Plitzko, S., & Bäger, D. (2023). Investigation of the Tendency of Carbon Fibers to Disintegrate into Respirable Fiber-Shaped Fragments. *Fibers*, 11(6). <https://doi.org/10.3390/fib11060050>
- Mie, G. (1908). Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösungen. *Annalen Der Physik*, 330(3), 377–445. <https://doi.org/10.1002/ANDP.19083300302>
- Mirata, S., Almonti, V., Di Giuseppe, D., Fornasini, L., Raneri, S., Vernazza, S., Bersani, D., Gualtieri, A. F., Bassi, A. M., & Scarfì, S. (2022). The Acute Toxicity of Mineral Fibres: A Systematic In Vitro Study Using Different THP-1 Macrophage Phenotypes. *International Journal of Molecular Sciences*, 23(5). <https://doi.org/10.3390/ijms23052840>
- Murray, R. (1990). Asbestos: A chronology of its origins and health effects. In *British Journal of Industrial Medicine* (Vol. 47, Number 6, pp. 361–365). <https://doi.org/10.1136/oem.47.6.361>
- National Cancer Institute. (2001). *Respiratory System: Image Details - NCI Visuals Online*. <https://visualsonline.cancer.gov/details.cfm?imageid=1773>
- Newman, S. (1985). *Aerosol Deposition Considerations in Inhalation Therapy*.

- Nieminen, T. A., Loke, V. L. Y., Stilgoe, A. B., Heckenberg, N. R., & Rubinsztein-Dunlop, H. (2011). T-matrix method for modelling optical tweezers. *Journal of Modern Optics*, 58(5–6), 528–544. <https://doi.org/10.1080/09500340.2010.528565>
- Noonan, C. W. (2017). Environmental asbestos exposure and risk of mesothelioma. In *Annals of Translational Medicine* (Vol. 5, Number 11). AME Publishing Company. <https://doi.org/10.21037/atm.2017.03.74>
- Nousiainen, T., Muñoz, O., Lindqvist, H., Mauno, P., & Videen, G. (2011). Light scattering by large Saharan dust particles: Comparison of modeling and experimental data for two samples. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 112(3), 420–433. <https://doi.org/10.1016/J.JQSRT.2010.09.003>
- Nurowska, K., Mohammadi, M., Malinowski, S., & Markowicz, K. (2023). Applicability of the low-cost OPC-N3 optical particle counter for microphysical measurements of fog. *Atmospheric Measurement Techniques*, 16(9), 2415–2430. <https://doi.org/10.5194/AMT-16-2415-2023>
- Paris, O., & Peterlik, H. (2009). The structure of carbon fibres. In *Handbook of Textile Fibre Structure* (Vol. 2, pp. 353–377). Elsevier Inc. <https://doi.org/10.1533/9781845697310.3.353>
- Pastuszka, J. S. (2009). Emission of airborne fibers from mechanically impacted asbestos-cement sheets and concentration of fibrous aerosol in the home environment in Upper Silesia, Poland. *Journal of Hazardous Materials*, 162(2–3), 1171–1177. <https://doi.org/10.1016/j.jhazmat.2008.06.045>
- Pastuszka, J. S., Kabala-Dzik, A., & Paw, K. T. (1999). A study of fibrous aerosols in the home environment in Sosnowiec, Poland. In *The Science of the Total Environment* (Vol. 229).
- Powers, S. R., & Somerford, D. J. (1978a). *FIBRE SIZING USING FRAUNHOFER DIFFRACTION* (Vol. 26).
- Powers, S. R., & Somerford, D. J. (1978b). Fibre sizing using Fraunhofer diffraction. *Optics Communications*, 26(3), 313–317. [https://doi.org/10.1016/0030-4018\(78\)90209-2](https://doi.org/10.1016/0030-4018(78)90209-2)
- Purcell, E. M., & Pennypacker, C. R. (1973). SCATTERING AND ABSORPTION OF LIGHT BY NONSPHERICAL DIELECTRIC GRAINS. In *The Astrophysical Journal* (Vol. 186).
- Rabiee, A., Della Ventura, G., Mirzapour, F., Malinconico, S., Bellagamba, S., Lucci, F., & Paglietti, F. (2023). Deep learning for asbestos counting. *Journal of Hazardous Materials*, 455. <https://doi.org/10.1016/j.jhazmat.2023.131590>
- Reid, J. S., Jonsson, H. H., Maring, H. B., Smirnov, A., Savoie, D. L., Cliff, S. S., Reid, E. A., Livingston, J. M., Meier, M. M., Dubovik, O., & Tsay, S. C. (2003). Comparison of size and morphological measurements of coarse mode dust particles from Africa. *Journal of Geophysical Research: Atmospheres*, 108(19). <https://doi.org/10.1029/2002jd002485>
- Romadhon, M. S., Peters, D., & Grainger, R. G. (2023). SPARCLE 2: A new optical particle counter to measure particle size and refractive index. *Atmospheric Measurement Techniques*. <https://doi.org/10.5194/amt-2023-140>
- Rood, A. P., Walker, E. J., & Moore, D. (1992). Construction of a portable fiber monitor measuring the differential light scattering from aligned fibers. *Aerosol Science and Technology*, 17(1), 1–8. <https://doi.org/10.1080/02786829208959555>

- Ross, M., & Nolan, R. P. (2003). History of asbestos discovery and use and asbestos-related disease in context with the occurrence of asbestos within ophiolite complexes. *Geological Society of America*, (373).
- Ruske, S., Topping, D. O., Foot, V. E., Kaye, P. H., Stanley, W. R., Crawford, I., Morse, A. P., & Gallagher, M. W. (2017). Evaluation of machine learning algorithms for classification of primary biological aerosol using a new UV-LIF spectrometer. *Atmospheric Measurement Techniques*, 10(2), 695–708. <https://doi.org/10.5194/amt-10-695-2017>
- Sarfraz, A., Simo, A., Fenger, R., Christen, W., Rademann, K., Panne, U., & Emmerling, F. (2012). Morphological diversity of caffeine on surfaces: Needles and hexagons. *Crystal Growth and Design*, 12(2), 583–588. https://doi.org/10.1021/CG101358Q/SUPPL_FILE/CG101358Q_SI_001.PDF
- Schäfer, J., Lee, S. C., & Kienle, A. (2012). Calculation of the near fields for the scattering of electromagnetic waves by multiple infinite cylinders at perpendicular incidence. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 113(16), 2113–2123. <https://doi.org/10.1016/J.JQSRT.2012.05.019>
- Schäfer, J. P. (2011). *Implementierung und Anwendung analytischer und numerischer Verfahren zur Lösung der Maxwellgleichungen für die Untersuchung der Lichtausbreitung in biologischem Gewebe*. Universität Ulm.
- Schmidt, V., Doicu, A., & Wriedt, T. (2009). *User's guide: T-matrix program based on the null-field method with discrete sources (NFM-DS)*.
- Schneider, T., Burdett, G., Martinon, L., Brochard, P., Guillemin, M., Teichert, U., & Draeger, U. (1996). Ubiquitous fiber exposure in selected sampling sites in Europe. In *Scandinavian Journal of Work* (Vol. 22, Number 4).
- Sen, D. (2015). Working with asbestos and the possible health risks. In *Occupational Medicine* (Vol. 65, Number 1, pp. 6–14). Oxford University Press. <https://doi.org/10.1093/occmed/kqu175>
- Smith, H. R., Ulanowski, Z., Kaye, P. H., Hirst, E., Stanley, W., Kaye, R., Wieser, A., Stopford, C., Kezoudi, M., Girdwood, J., Greenaway, R., & Mackenzie, R. (2019). The Universal Cloud and Aerosol Sounding System (UCASS): A low-cost miniature optical particle counter for use in dropsonde or balloon-borne sounding systems. *Atmospheric Measurement Techniques*, 12(12), 6579–6599. <https://doi.org/10.5194/AMT-12-6579-2019>
- Somtürk, S. M., Emek, I. Y., Senler, S., Eren, M., Kurt, S. Z., & Orbay, M. (2016). Effect of wollastonite extender on the properties of exterior acrylic paints. *Progress in Organic Coatings*, 93, 34–40. <https://doi.org/10.1016/J.PORGCOAT.2015.12.014>
- Spurny, K. R. (1994). Sampling, Analysis, Identification and Monitoring of Fibrous Dusts and Aerosols*. *Analyst*, 11, 41.
- Stopford, C. (2010). *Ice Crystal Classification Using Two Dimensional Light Scattering Patterns*. <http://uhra.herts.ac.uk/handle/2299/4797>
- Stopford, C., Kaye, P. H., Greenaway, R. S., Hirst, E., Ulanowski, Z., & Stanley, W. R. (2013). Real-time detection of airborne asbestos by light scattering from magnetically re-aligned fibers. *Optics Express*, 21(9), 11356. <https://doi.org/10.1364/oe.21.011356>

- Susz, A., Pratte, P., & Goujon-Ginglinger, C. (2020). Real-time monitoring of suspended particulate matter in indoor air: Validation and application of a light-scattering sensor. *Aerosol and Air Quality Research*, 20(11), 2384–2395. <https://doi.org/10.4209/aaqr.2019.11.0604>
- Thomason, J. L. (2019). Glass fibre sizing: A review. In *Composites Part A: Applied Science and Manufacturing* (Vol. 127). Elsevier Ltd. <https://doi.org/10.1016/j.compositesa.2019.105619>
- Thorpe, A. (2007). Assessment of personal direct-reading dust monitors for the measurement of airborne inhalable dust. *Annals of Occupational Hygiene*, 51(1), 97–112. <https://doi.org/10.1093/annhyg/mel032>
- Uibu, T., Oksa, P., Auvinen, A., Honkanen, E., Metsärinne, K., Saha, H., Uitti, J., & Roto, P. (2004). Asbestos exposure as a risk factor for retroperitoneal fibrosis. *Lancet*, 363(9419), 1422–1426. [https://doi.org/10.1016/S0140-6736\(04\)16100-X](https://doi.org/10.1016/S0140-6736(04)16100-X)
- Ulanowski, Z., Kaye, P. H., Hirst, E., Greenaway, R. S., Cotton, R. J., Hesse, E., & Collier, C. T. (2014). Incidence of rough and irregular atmospheric ice particles from Small Ice Detector 3 measurements. *Atmospheric Chemistry and Physics*, 14(3), 1649–1662. <https://doi.org/10.5194/acp-14-1649-2014>
- Van Der Meulen, A., & Strackee, L. (1979). *Accurate determination of fiber radii in the hypermicrometer range by multiwavelength laser light scattering*.
- Verma, D. K., Sahai, D., Kurtz, L. A., & Finkelstein, M. M. (2004). Current Man-Made Mineral Fibers (MMMF) Exposures Among Ontario Construction Workers. *Journal of Occupational and Environmental Hygiene*, 1(5), 306–318. <https://doi.org/10.1080/15459620490445462>
- Wang, A., Gupta, A., Grimm, M. D., Pressburger, D. T., Sparrow, B. R., Richey, J. S., Shaw, J. R., Elsass, K. E., Roberts, G. K., Yao, P. L., Stout, M. D., Ellis, B. J., & Ray, R. L. (2023a). Natural mineral fibers: conducting inhalation toxicology studies—part A: Libby Amphibole aerosol generation and characterization method development. *Inhalation Toxicology*, 35(7–8), 201–213. <https://doi.org/10.1080/08958378.2023.2220737>
- Wang, A., Gupta, A., Grimm, M. D., Pressburger, D. T., Sparrow, B. R., Richey, J. S., Shaw, J. R., Elsass, K. E., Roberts, G. K., Yao, P. L., Stout, M. D., Ellis, B. J., & Ray, R. L. (2023b). Natural mineral fibers: conducting inhalation toxicology studies—part B: development of a nose-only exposure system for repeat-exposure in vivo study of Libby amphibole aerosol. *Inhalation Toxicology*, 35(7–8), 214–229. <https://doi.org/10.1080/08958378.2023.2220735>
- Waterman, P. C. (1965). *Matrix Formulation of Electromagnetic Scattering*.
- Waterman, P. C. (1969). New Formulation of Acoustic Scattering. *The Journal of the Acoustical Society of America*, 45(6), 1417–1429. <https://doi.org/10.1121/1.1911619>
- Waterman, P. C. (1971). Symmetry, Unitarity, and Geometry in Electromagnetic Scattering*. *Physical Review D*, 3(4), 825–839.
- Waterman, P. C. (2007). The T-matrix revisited. *JOSA A*, Vol. 24, Issue 8, Pp. 2257–2267, 24(8), 2257–2267. <https://doi.org/10.1364/JOSAA.24.002257>
- Watkins, L. S. (1974). *Scattering from side-illuminated clad glass fibers for determination of fiber parameters*.

- West, E. A., Porter, J. G., Davis, J. M., Gary, G. A., Noble, M. W., Lewis, M., Thomas, R. J., Bridou, ; F, Cuniot-Ponsard, M., Desvignes, J. M., Gottwald, A., Kroth, U., Richter, M., Zukic, ; M, Torr, D. G., Spann, J. F., & Torr, M. R. (2016). Self-consistent optical constants of SiO_2 and Ta_2O_5 films. *Optical Materials Express*, Vol. 6, Issue 11, Pp. 3622-3637, 6(11), 3622–3637. <https://doi.org/10.1364/OME.6.003622>
- Wieder, J. (2018). *The high-speed particle phase discriminator - PPD-HS*. <https://doi.org/10.3929/ETHZ-B-000566869>
- World Health Organisation. (1985). *REFERENCE METHODS FOR MEASURING AIRBORNE MAN-MADE MINERAL FIBRES (MMM) WHO/EURO MMM Reference Scheme Monitoring Concentration using a Phase Contrast Optical Microscope Determining Size using a Scanning Electron Microscope prepared by the WHO/EURO Technical Committee for Monitoring and Evaluating Airborne MMM WORLD HEALTH ORGANIZATION Regional Office for Europe COPENHAGEN 1985*.
- World Health Organisation. (1997). *Determination off Airborne Fibre Number Concentrations*.
- Wriedt, T. (2002). *Using T-Matrix Method for Light Scattering Computations by Non-axisymmetric Particles: Superellipsoids and Realistically Shaped Particles* (Vol. 28).
- Yurkin, M. A., & Hoekstra, A. G. (2007). *The discrete dipole approximation: an overview and recent developments*.
- Yurkin, M. A., & Hoekstra, A. G. (2011). The discrete-dipole-approximation code ADDA: Capabilities and known limitations. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 112(13), 2234–2247. <https://doi.org/10.1016/j.jqsrt.2011.01.031>
- Yurkin, M. A., & Hoekstra, A. G. (2020). *User Manual for the Discrete Dipole Approximation Code ADDA 1.4.0*. <https://github.com/adda-team/adda/raw/v1.4.0/doc/manual.docx> and <https://github.com/adda-team/adda/tree/v1.4.0/doc/figs>, respectively.
- Zhang, T., Ruan, Y., Maire, G., Sentenac, D., Talneau, A., Belkebir, K., Chaumet, P. C., & Sentenac, A. (2013). Full-polarized tomographic diffraction microscopy achieves a resolution about one-fourth of the wavelength. *Physical Review Letters*, 111(24). <https://doi.org/10.1103/PHYSREVLETT.111.243904>
- Zhang, X. H., & Li, Q. W. (2017). Carbon fiber spinning. In *Activated Carbon Fiber and Textiles* (pp. 39–60). Elsevier Inc. <https://doi.org/10.1016/B978-0-08-100660-3.00003-1>

7 Appendix

7.1 Fourier Transform Explanation

A Fourier transform is essentially a decomposition of a wave function into its constituent waves that combine to make that function, represented by their frequencies and amplitudes. Figure 7.1 (left) shows examples of two different waves (dashed lines) and their resulting combination (solid blue lines). Right of Figure 7.1 is the absolute values of the Fourier transforms of each of those waves, colours corresponding to the waves on the left plot of Figure 7.1. It is apparent that the combination of the Fourier transforms of wave A (orange) and wave B (yellow) result in the top right plot of Figure 7.1.

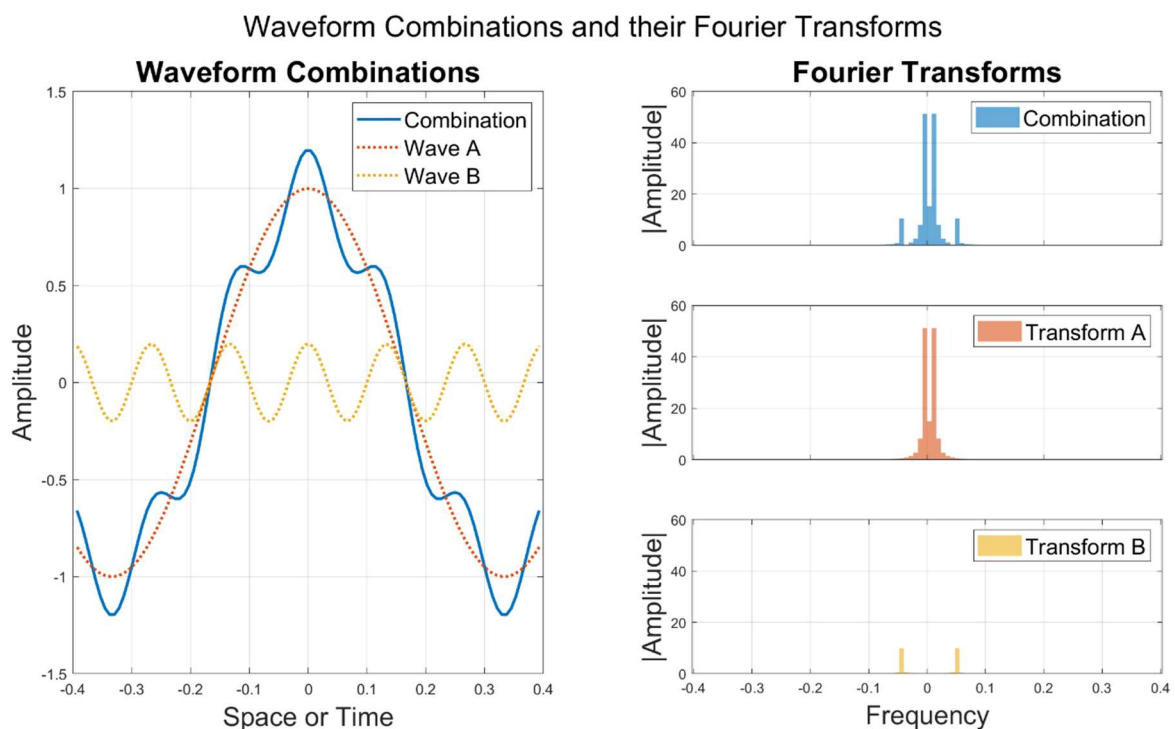


Figure 7.1: Examples (left) of two different waveforms (dashed lines) and their combined wave (solid blue) and their corresponding Fourier transforms (right) showing the absolute value for each waveform as discrete bars.

Each spike of the Fourier transform plots of Figure 7.1 (top right) represent each wave that combines to create the resulting waveform (Figure 7.1, right, solid blue line), the spikes are mirrored about the y-axis at zero due to the waves periodic nature.

The x-axis of Figure 7.1 (left) indicates space or time, this is because they are essentially the same. The waveform can represent cyclical variations in both time and space, the wavelength (λ) indicating the length of a single cycle. The frequency of the waveform, i.e., the number of cycles completed over a unit time or length, is the reciprocal of the wavelength (λ^{-1}), with units of either inverse time or length.

The concept of temporal frequency is used regularly in subjects regarding physics, e.g. the frequency of a light wave oscillating over time has the units s^{-1} , i.e. *Hz*. Spatial frequency, however, seems much more confusing due to the units of L^{-1} , where L is a unit of length. Simply, as the time example used describes the frequency as number of wave oscillations per

second, a spatial example would be number of repeated patterns per unit length. As an example, Figure 7.2 shows two different waves, oscillating over a length L . The plot on the left of Figure 7.2 completes one oscillation between 0 and L , the one on the right completes five, resulting in spatial frequencies of 1 and 5 respectively.

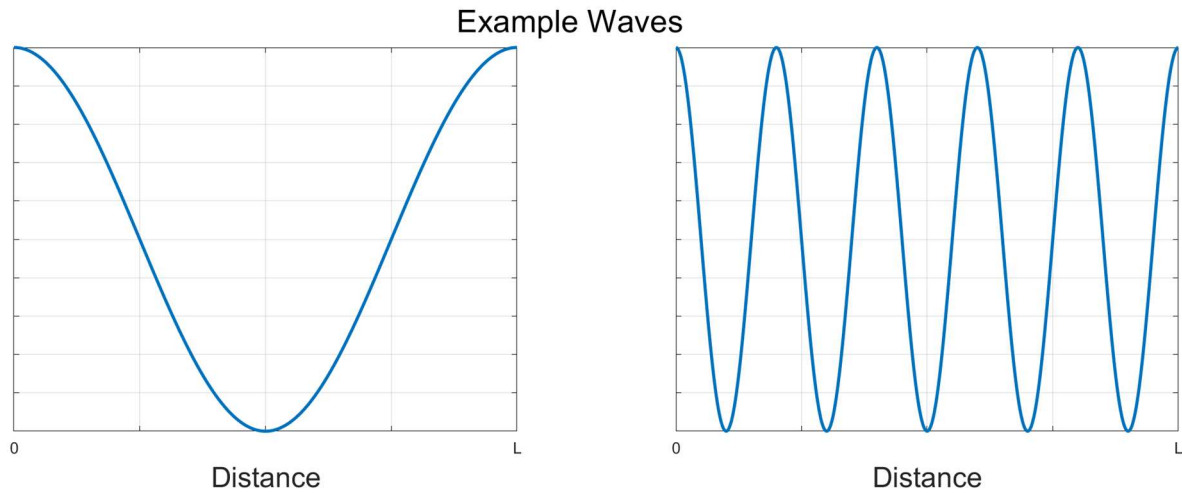


Figure 7.2: Examples of two different waves of different spatial frequencies. The left shows a single oscillation over a distance L , having a spatial frequency of 1. The right shows five oscillations over a distance L , having a spatial frequency of 5.

When considering the example used in this work, a square pulse, it can be approximated by a series of cosine functions. This approximation is used due to the infinite number of cosine functions required for a true square pulse. Each of these functions can be represented in the frequency domain, using the Fourier transform. Figure 7.3 shows examples of a square pulse approximation of varying orders (left column), the corresponding Fourier transforms (middle column), and the absolute value of those transforms (right column). As the number of orders increase, i.e., approaches infinity, the more the Fourier transforms resemble the continuous sinc function.

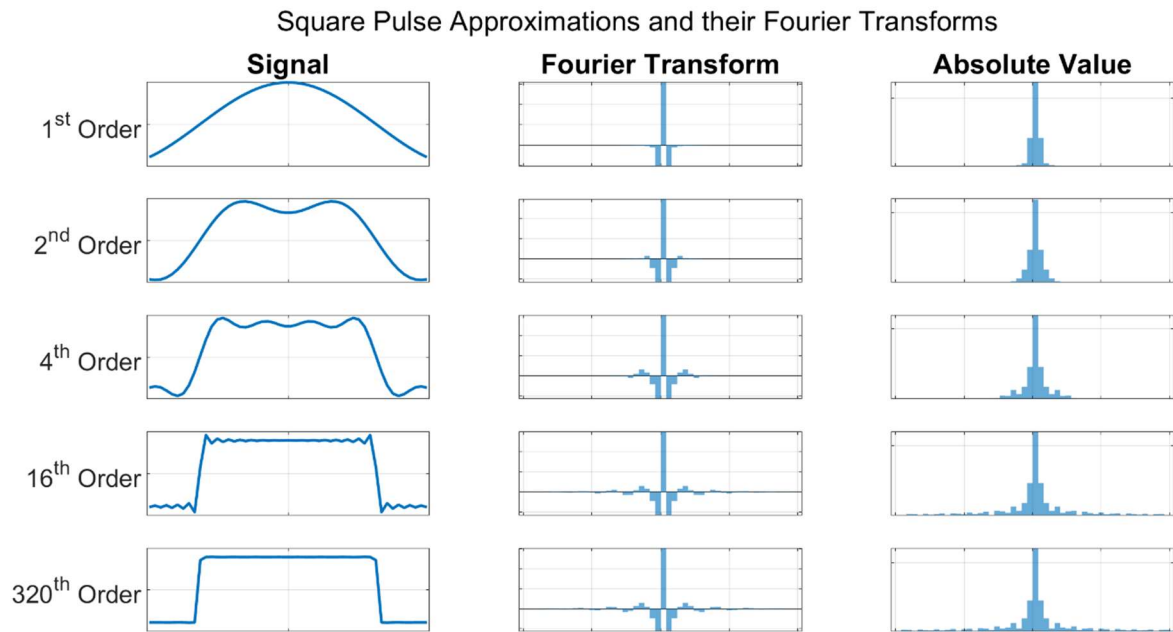


Figure 7.3: Demonstration of the approximation of a square pulse using the combination of cosine functions (right column) with increasing orders from top to bottom. The middle and left show the corresponding Fourier transforms and absolute values thereof respectively.

The square pulse and resulting Fourier transform is not, however, an infinitely long slit and the diffraction pattern produced, but a representation of that system.

7.2 Static Fibre Experiment Results

The following includes the complete 180° scattering results of the two fibre samples from the experiment detailed in Chapter 3.

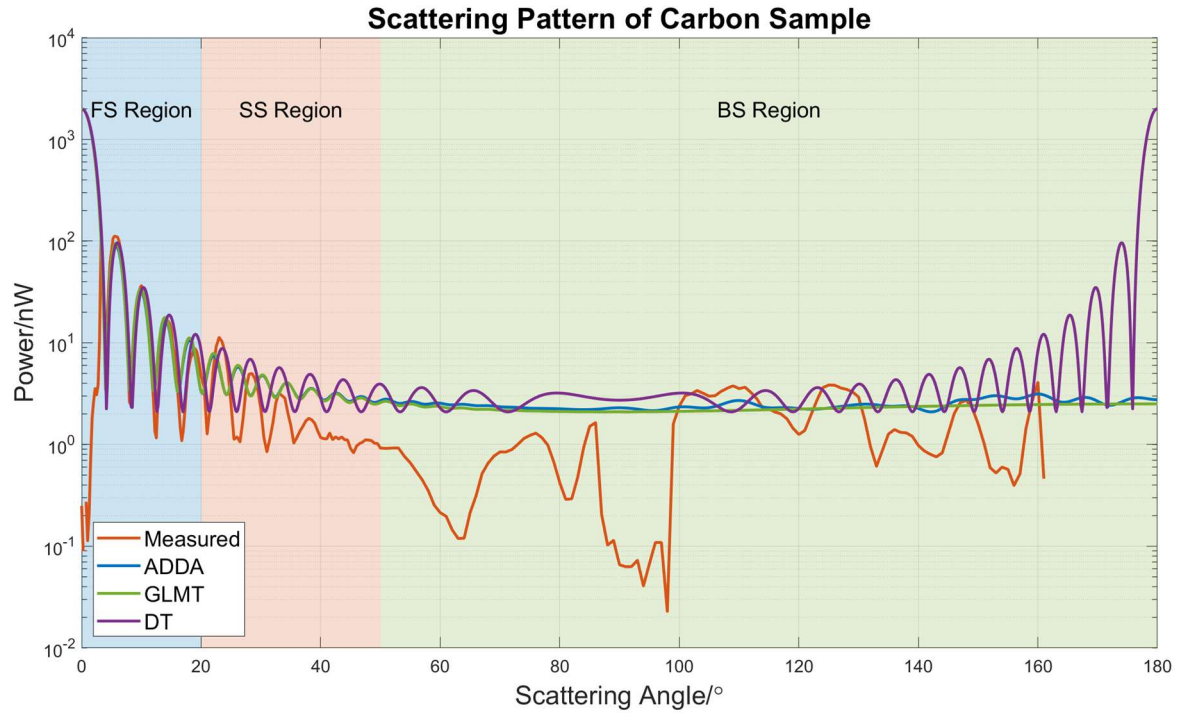


Figure 7.4: Scattering results of carbon fibre scattering experiment compared with results of models plotted on a logarithmic scale for the power against the scattering angle. The forward scattering (FS), side scattering (SS), and back scattering (BS) regions are shaded blue, red, and green respectively

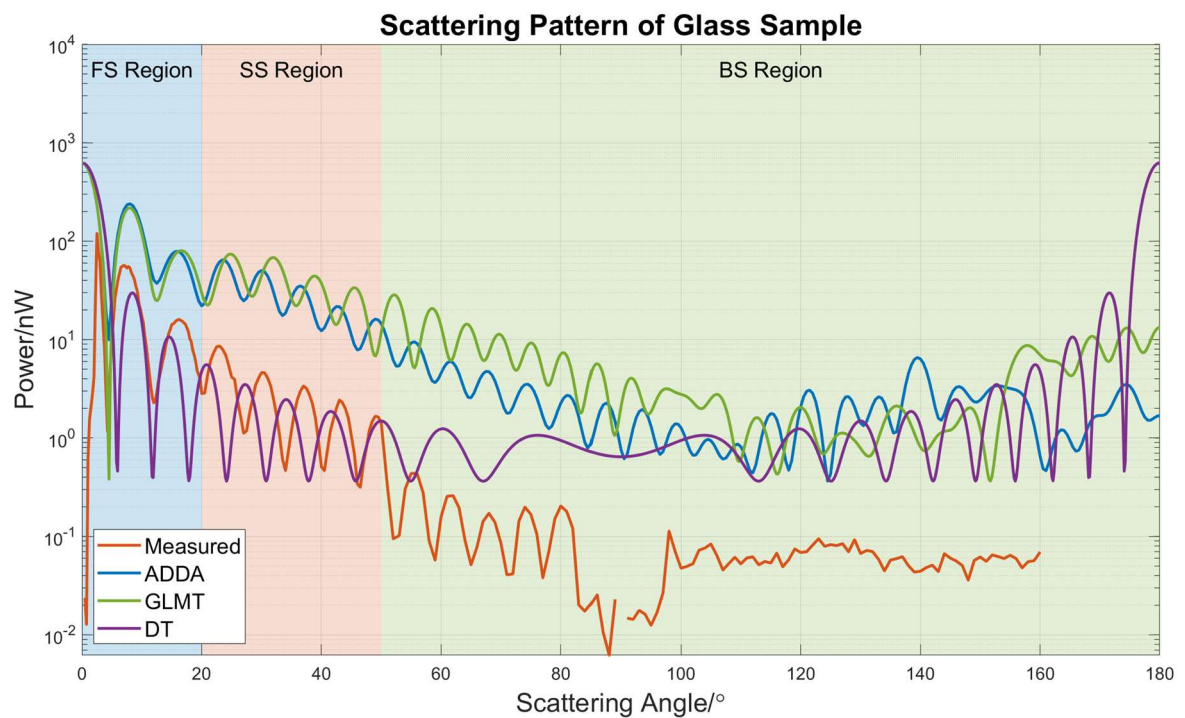


Figure 7.5: Scattering results of glass fibre scattering experiment compared with results of models plotted on a logarithmic scale for the power against the scattering angle. The forward scattering (FS), side scattering (SS), and back scattering (BS) regions are shaded blue, red, and green respectively.

7.3 Chapter 4 Supplementary

The following contains the additional plots from the investigation conducted in Chapter 4.

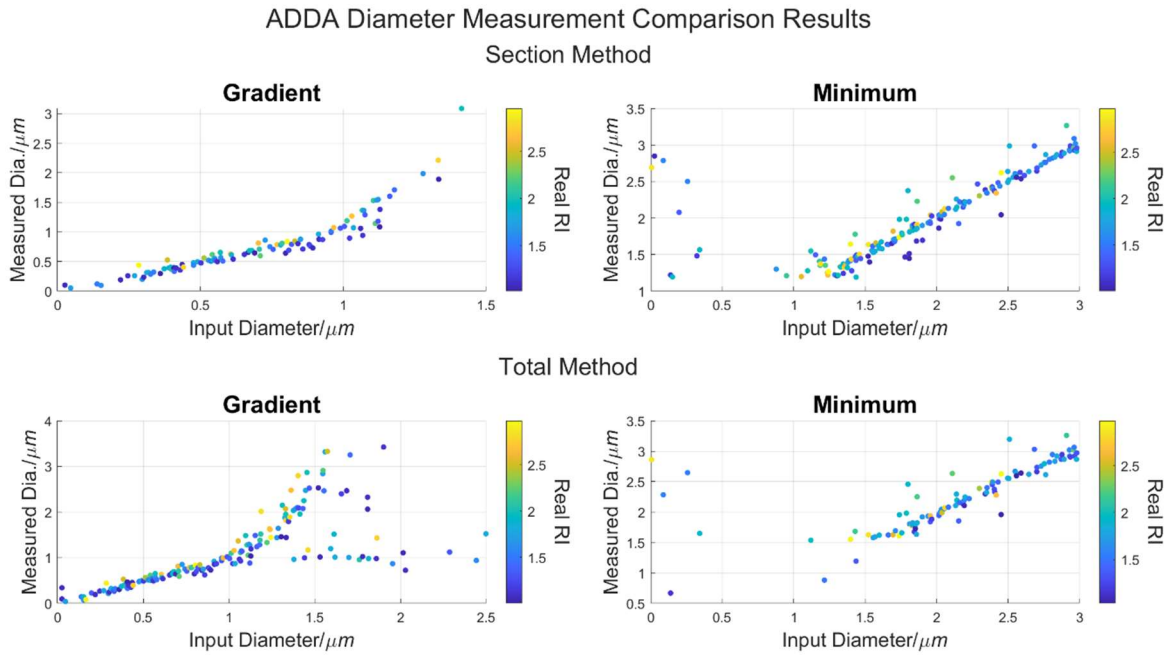


Figure 7.6: Diameter measurement results from ADDA modelled data using the section method (top) and the total method (bottom). The plots on the left-hand side show the diameter results using the gradient method and the plots on the right-hand side show the results of the minimum method. The scatter points are colour-coded to the real part of the refractive index, shown as a colour bar on the right-hand side of the plots.

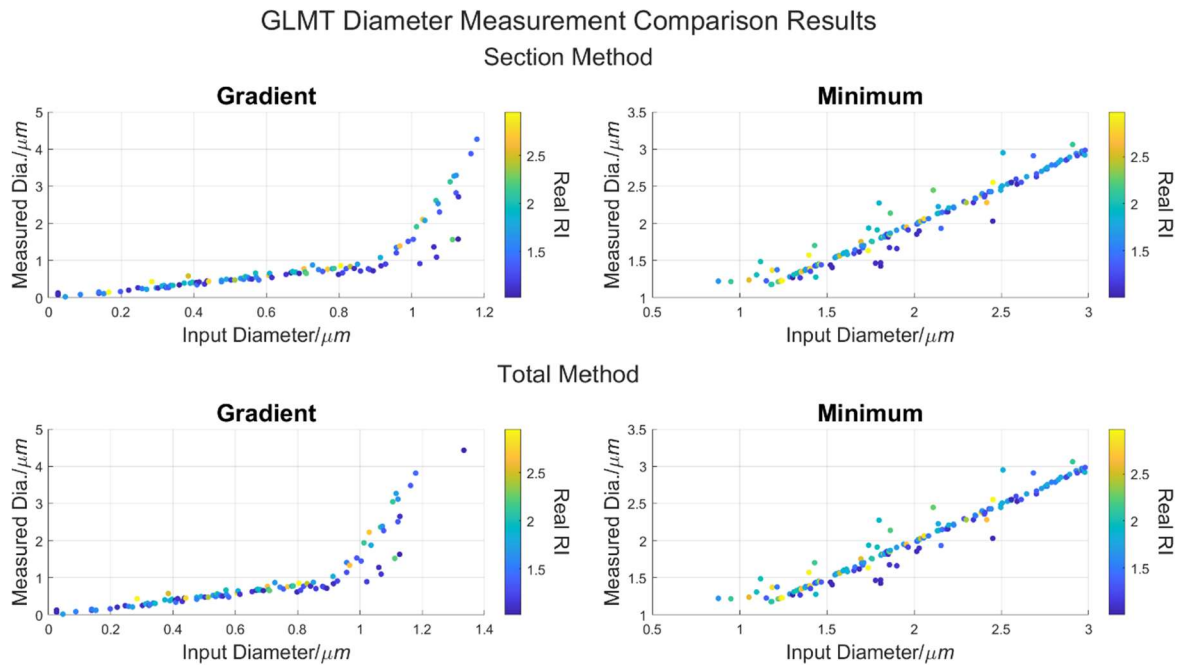


Figure 7.7: Diameter measurement results from GLMT modelled data using the section method (top) and the total method (bottom). The plots on the left-hand side show the diameter results using the gradient method and the plots on the right-hand side show the results of the minimum method. The scatter points are colour-coded to the real part of the refractive index, shown as a colour bar on the right-hand side of the plots.

ADDA Length Measurement Comparison Results

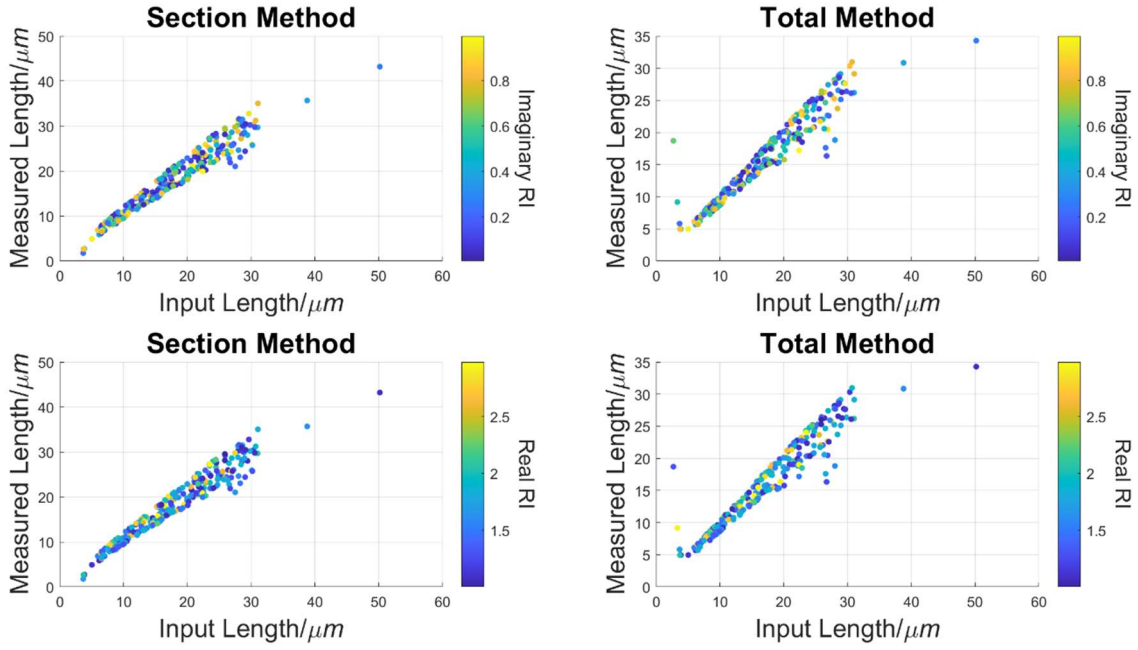


Figure 7.8: Length measurement results from ADDA modelled data using the section method (left) and the total method (right). The plots on the top show the length results colour-coded using the imaginary part of the refractive index and the plots on the bottom show the results colour-coded using the real part of the refractive index.

GLMT Length Measurement Comparison Results

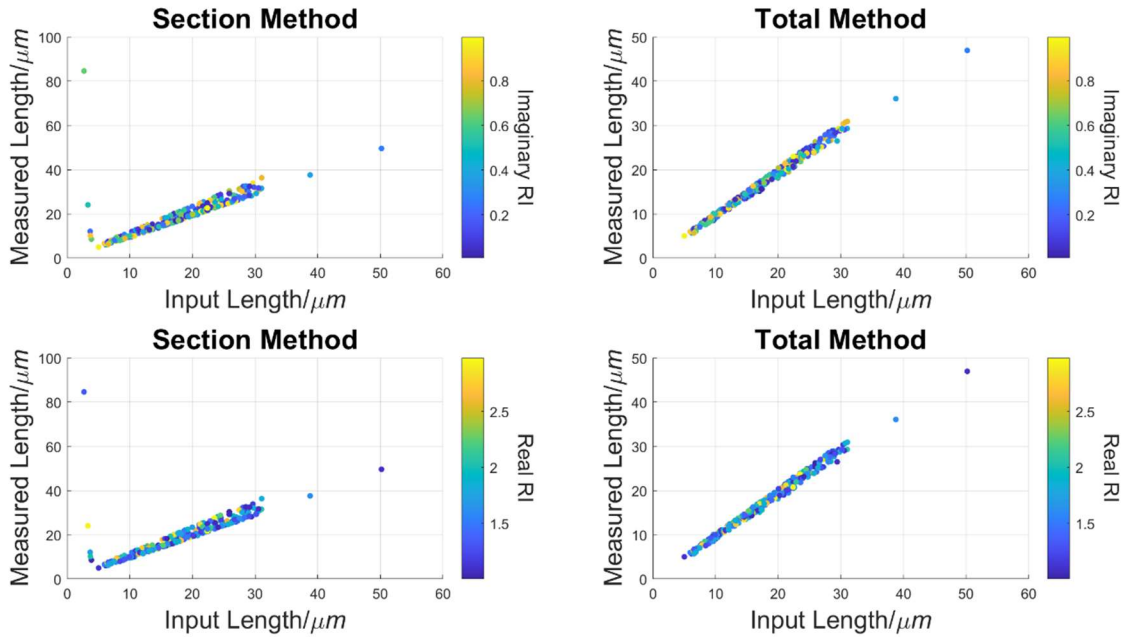


Figure 7.9: Length measurement results from GLMT modelled data using the section method (left) and the total method (right). The plots on the top show the length results colour-coded using the imaginary part of the refractive index and the plots on the bottom show the results colour-coded using the real part of the refractive index.

ADDA Length Measurement Comparison Results

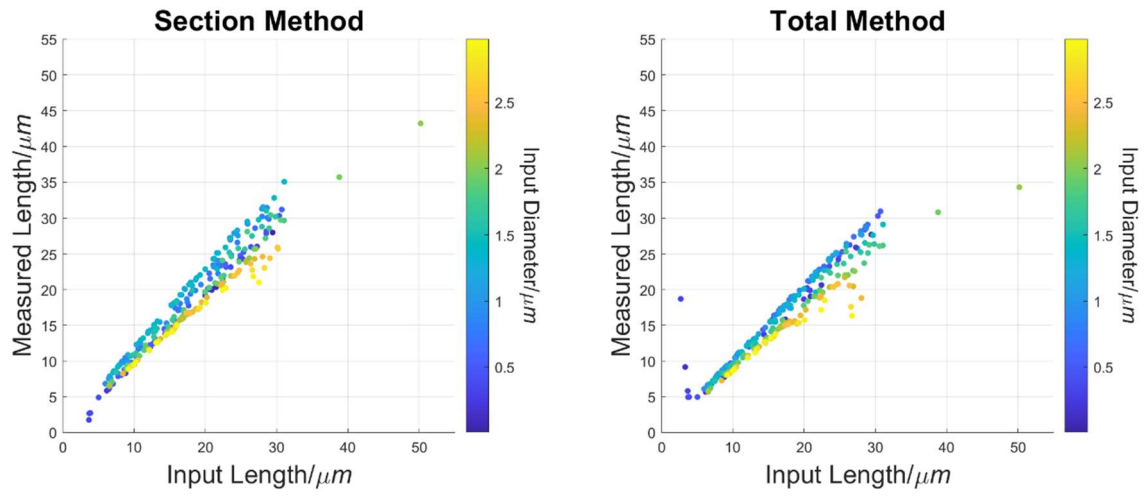


Figure 7.10: Length measurement results from ADDA modelled data using the section method (left) and the total method (right). The results are colour-coded using input diameter.

GLMT Length Measurement Comparison Results

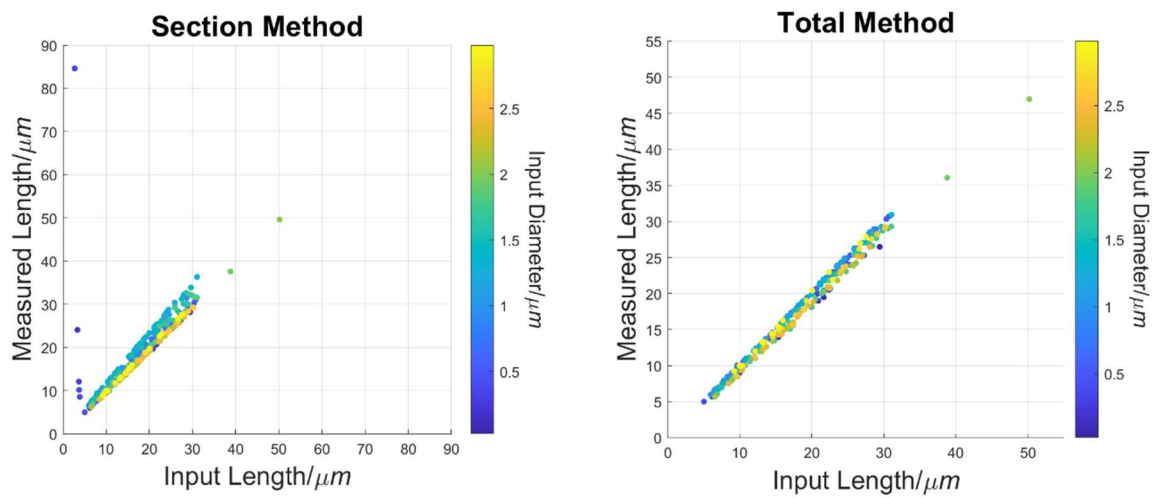


Figure 7.11: Length measurement results from GLMT modelled data using the section method (left) and the total method (right). The results are colour-coded using input diameter.

Measured and Reference Diameter Comparisons for GLMT-Modelled Scattering Images

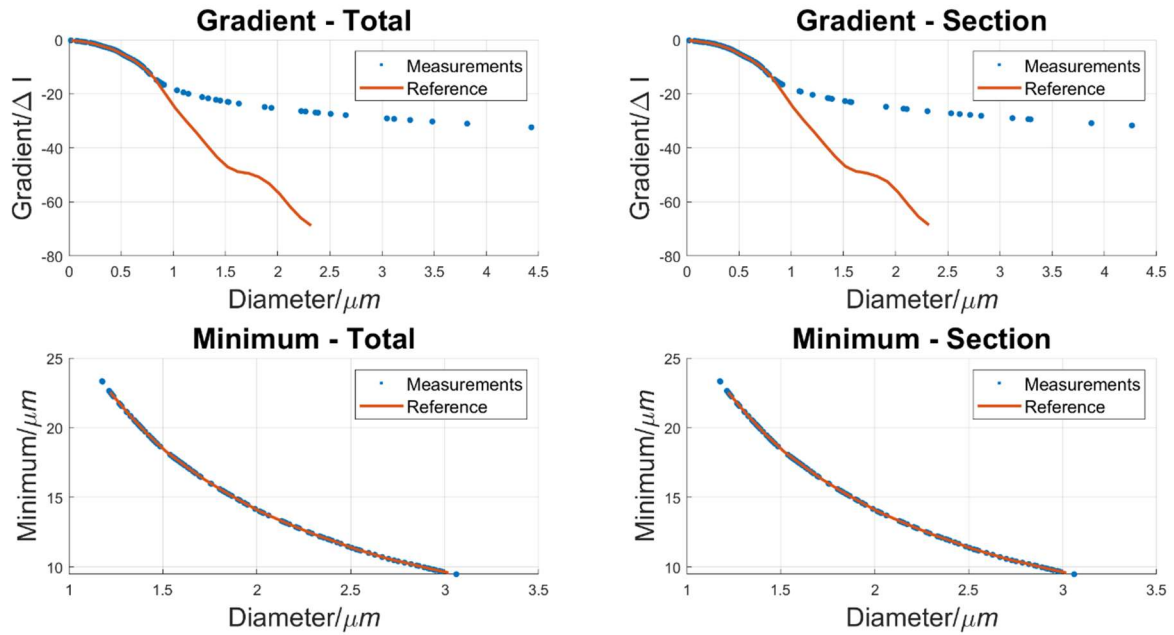


Figure 7.12: Comparisons of the measured and reference diameters from the GLMT-modelled data. Top row shows the reference data (orange) for the gradient measurements for both the total and section methods (left and right respectively). Overlaid (blue dots) are the gradient measurements plotted against the measured diameter. The bottom row shows the same results but for the minimum measurements.

7.4 Software and Algorithm Description

7.4.1 Image Processing

Before any measurements for both the reference data or the scattering data can be made, the simulated data needs to be processed into reference images and the scattering images also need to be processed.

7.4.1.1 Modelled Data

This code takes the raw modelled data to create scattering images that resemble data measured by PPD2. This is the first step in the creation of the reference data.

First, directories are chosen that contain the required data set, these are all separated into groups of changing variables, such as diameters and lengths. An output file is also selected for the reference images to be saved to. The modelled data is in the form⁵⁵ of a Mueller matrix⁵⁶, and this code uses the S_{11} cell for the creation of the images. The total S_{11} scattering for a cylindrical scatterer is shown in Figure 7.13 (left).

⁵⁵ This is true for most models but not GLMT – this is explained in Section 2.3.

⁵⁶ See Section 1.5.4.

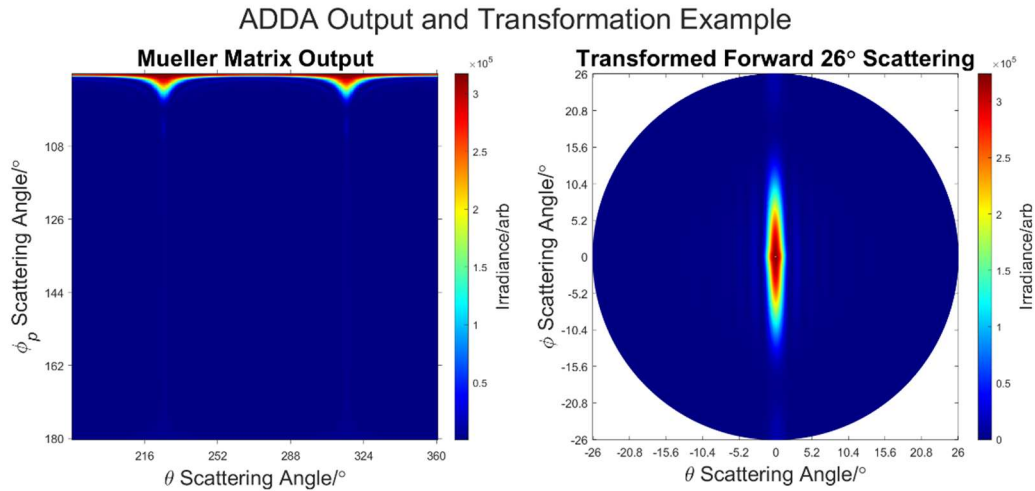


Figure 7.13: ADDA modelled data example of the Mueller matrix output, organised into a θ by ϕ_p grid (left) and transformed into the forward 26° scattering (right).

A function then used the matrix and, with predefined parameters, transforms the matrix into something that resembles data collected by PPD – shown in Figure 7.13 (right). The predefined parameters are the angular limit of PPD, the outer angular limit⁵⁷ being set to 26° . The function creates three matrices that are then used in a pseudo-colour plot in MatLab that is then automatically saved to file as a png image with its' information of size and refractive index as the file name – to be read and used in subsequent code.

As mentioned in Section 2.5.2, MatLab has no easy method of creating polar plot for images and so the output matrix, shown in Figure 7.13 (left), is converted into a cartesian coordinate system in order to display the data as shown in Figure 7.13 (right). The polar angle ϕ_p is only used to describe the Mueller matrix output and the angle ϕ is used to describe any scattering features after the transformation, as described in Section 1.5.5.

7.4.1.2 PPD Data

This code first reads the directories of where the PPD2 data has been saved and creates a new folder, if required, for the resulting processed data. It also was intended to create subsequent subfolders for categorisation of scattering patterns and automated to run through all data sets, however, the categorisation is still a work in progress and the automated processing takes a while so is not used.

For each sample the code reads each scattering image one at a time, each image is named using a unique timestamp from PPD2 to help with later problems and troubleshooting. The raw images are of size 582×768 pixels and are then cropped to make them square – shown in Figure D.2.

⁵⁷ This can be set to anything to suit the required scattering angle.

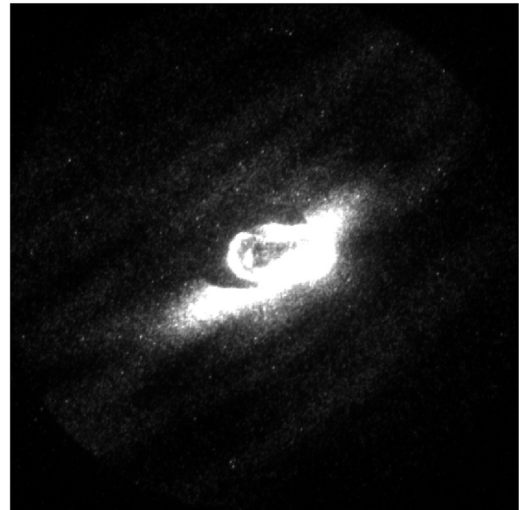
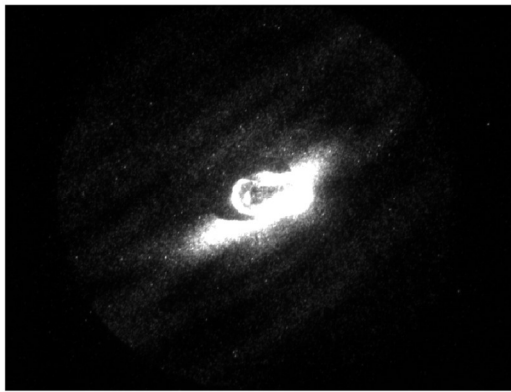


Figure 7.14: PPD2 example data before (left) and after (right) cropping into a square image.

The stray light of the beam-stop is then blocked to avoid interference with the measurements by setting the values of a circle in the centre of the matrix to zero. The image is then divided into segments about the centre, this is carried out using a mask. The mask is constructed from integer values equalling the number of segments – an example of 18 segments is shown in Figure D.2 (right), each segment is then used to divide the scattering image.

The pixel sum of each segment is then found to create a rudimentary radial intensity array. This array was originally thought of to be used as a method of differentiating between fibrous and non-fibrous scattering patterns, unfortunately, it requires more development but does prove useful in the re-orienting of the scattering patterns. Below shows an example of the radial intensity plot and the image and mask used to find it. Local maximum points are found in the array, that have to exceed a maximum prominence of the mean value of the array – this is to help reduce the number of maximum points found due to noise. For very well-defined fibrous scattering patterns a single or double peak is found.

Image Segmentation Example

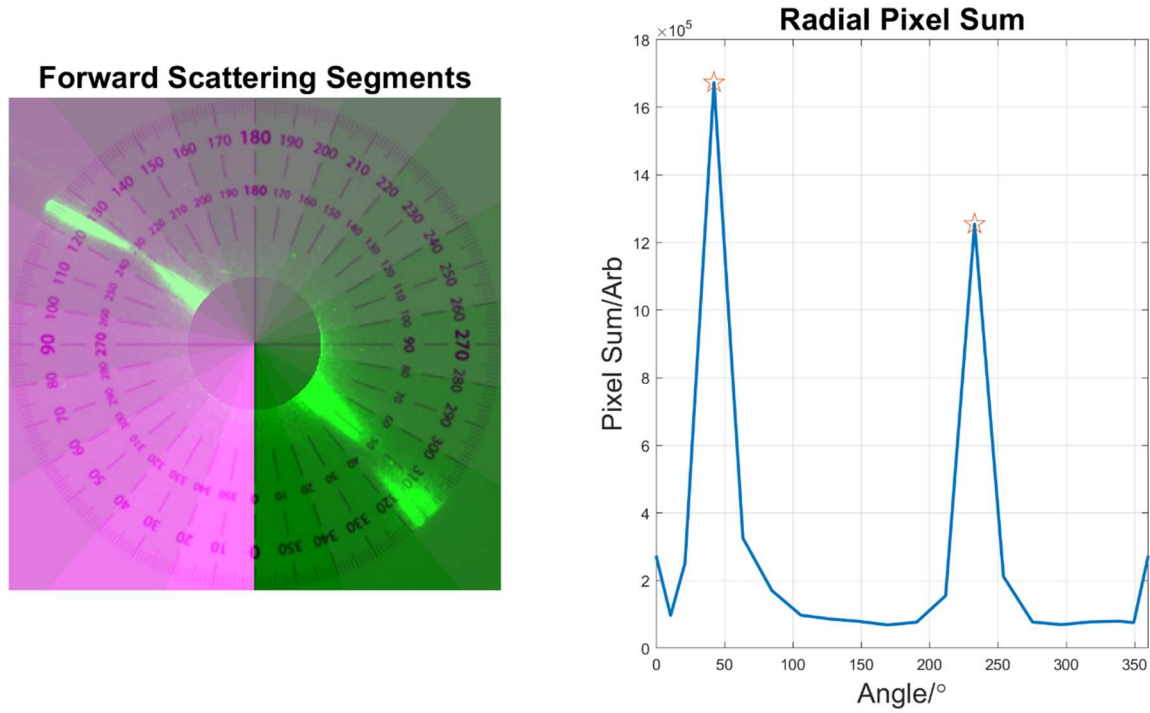


Figure 7.15: Segmentation example of scattering from a fibre, captured by PPD2 (left) and the pixel sum of each segment depending on rotational angle (right). NOTE: The angle markings on the scattering image (left) use the inside measurements shown for the radial sum (right).

The peaks were sorted and the highest was used to find the angle to re-orient the image. As some fibres can be already aligned with the start and end of the segments, a mean value is used as padding, without this the peaks would not be found. An example of the resulting radial intensity from the segmentation of the image is shown in Figure 7.15 (right).

The image is then rotated and another function is used to find the curvature of the bright band⁵⁸ of the scattering pattern of the fibre – if it is so. The rotation is made to align the bright scattering band vertically, or as close as possible, to account for the way the analysis of the image is made, described later.

7.4.1.3 Curve Fitting Algorithm

The curvature function, though currently unused, is an attempt at measuring the rotational orientation of the fibre, perpendicular to the propagation direction of the incident laser light. Previously, a non-linear relationship has been found from the curvature of the bright band and the angle of incidence – this is not the rotational orientation and is/has been explained in Chapter 4. This function works by finding the brightest points of the scattering that intersect with two circles, one smaller one near the centre of the image, and a larger one towards the edge. Four points are then found. The two outer points and one of the centre points are then used to fit a circle to the bright band using the following set of equations:

$$A = x_1(y_2 - y_3) - y_1(x_2 - x_3) + x_2y_3 - x_3y_2$$

$$B = (x_1^2 + y_1^2)(y_3 - y_2) + (x_2^2 + y_2^2)(y_1 - y_3) + (x_3^2 + y_3^2)(y_2 - y_1)$$

⁵⁸ Indication of β -angle orientation, see Section 1.5.6.

$$C = (x_1^2 + y_1^2)(x_2 - x_3) + (x_2^2 + y_2^2)(x_3 - x_1) + (x_1 - x_2)$$

$$D = (x_1^2 + y_1^2)(x_3y_2 - x_2y_3) + (x_2^2 + y_2^2)(x_1y_3 - x_3y_1) + (x_3^2 + y_3^2)(x_2y_1 - x_1y_2)$$

where the subscripts indicate the three different coordinates for the x axis and y axis of the image. The formulas A , B , C , and D are then used to find the radius of the circle R , and the coordinates of the circles centre (x_R, y_R) :

$$R = \sqrt{\frac{B^2 + C^2 - 4AD}{4A^2}}$$

$$x_R = -\frac{B}{2A}$$

$$y_R = -\frac{C}{2A}$$

As there are four points to be used to fit a circle, two measurements are made using the two outer points and one inner point each. For some shorter fibres that have quite a wide band, this sometimes results in very conflicting radii and centres. Ideas to improve on this are using the mean, although this can result in a mean value of zero, if symmetrical. Or by setting a threshold wherein if the two measurements are far removed from each other, the result is disregarded. The zero mean usually happens when the bright band is quite straight, resulting in near opposite centres and radii approaching infinity.

7.4.1.4 Image Categorisation

An attempt was made to categorise the different scattering types found automatically using different archetypical features of the different types. Unfortunately, efforts made showed miscategorisations and requires further investigation. Until then, a manual selection of scattering patterns was made to remove any obvious non-fibre scattering, agglomerates, or with extreme curvature from orientation. Additionally, bowtie patterns from curved fibres are also removed, as no method on measuring length has hitherto been found.

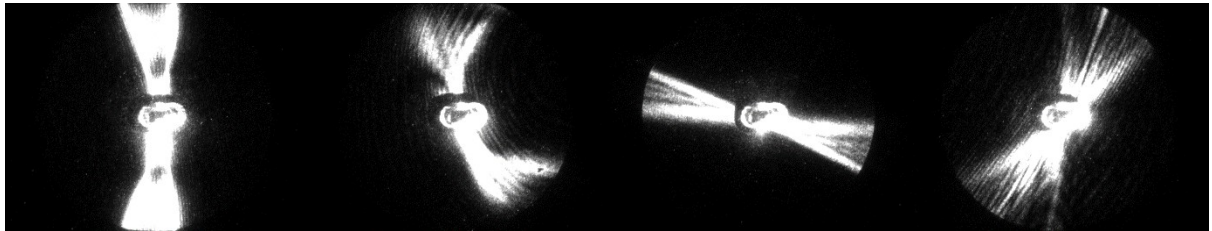


Figure 7.16: Examples of forward scattering patterns from curved fibres, captured by PPD2.

Figure 7.16 shows examples of the bowtie scattering from curved fibres captured by PPD2. Currently, length is measured using the full-width half-maximum value of the fibres bright band – previous simulations show a non-linear relationship (see Chapter 4). Using the FWHM to measure this fibre would prove wrong. Speculating into how the length measurement could be achieved may lie in the longitudinal fringes, curvature in the degree of spread from the centre to the edge, and diameter the same to what has previously been investigated. However, this needs much further investigation and is beyond the scope of this project.

7.4.2 Measurements

This section describes the methods involved in the measurement of both the reference and scattering data.

7.4.2.1 Processing Data

In addition to the explanation given in Section 4.3.1.4, both the modelled reference data and captured scattering data are measured in the same way. Considering diameter measurements, both sides of the scattering data are measured (gradient and minimum) and a mean of those measurements are recorded. The captured scattering from PPD2 requires filtering to reduce noise and different prominence thresholds are needed for captured and modelled data when finding the minimum points. For each image of the captured scattering data, the following measurements are written to file: minimum angles (left and right), gradient values (left and right), FWHM. The modelled data also includes the input variables in addition: diameter, length, refractive index, orientation. For each set a text file is created that contains these data.

7.4.2.2 Determining Measurements

Three sets of data are used to determine the measurements of the fibre, based on its scattering pattern – this explanation is in addition to that found in Section 4.3. Two of the three sets are the reference data, generated using the modelled scattering that contain both the input variables and the measured features. The third set is the data measured from the captured scattering images, which are then compared with those of the reference data to determine a most likely length and diameter.

7.5 Chapter 5 Supplementary Results

The following contains the additional plots used for the optimisation of the angular limits of the gradient measurement.

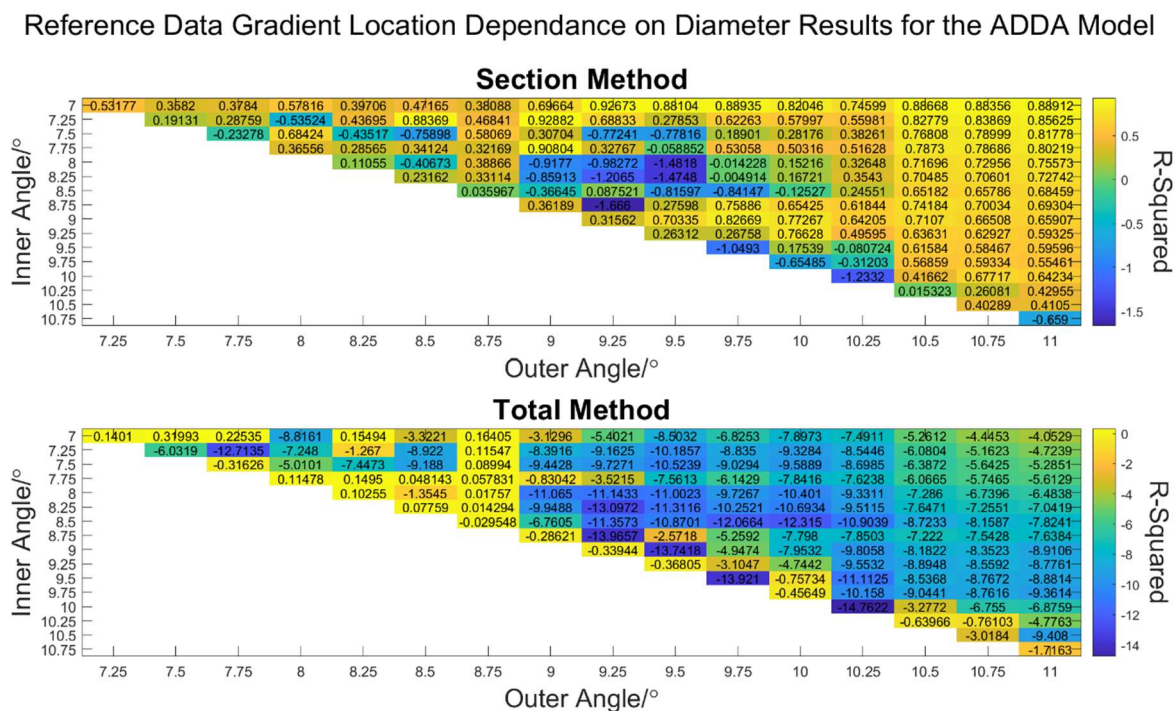


Figure 7.17: R-squared values for the gradient diameter measurement results compared to a function of $y = x$ for data modelled in ADDA. The top shows the results using the section method, the bottom shows the results using the

total method. The y-axis indicates the smaller angular limit, closer to the forward scattering direction, the x-axis indicates the larger angular limit.

Reference Data Gradient Location Dependence on Diameter Results for the GLMT Model

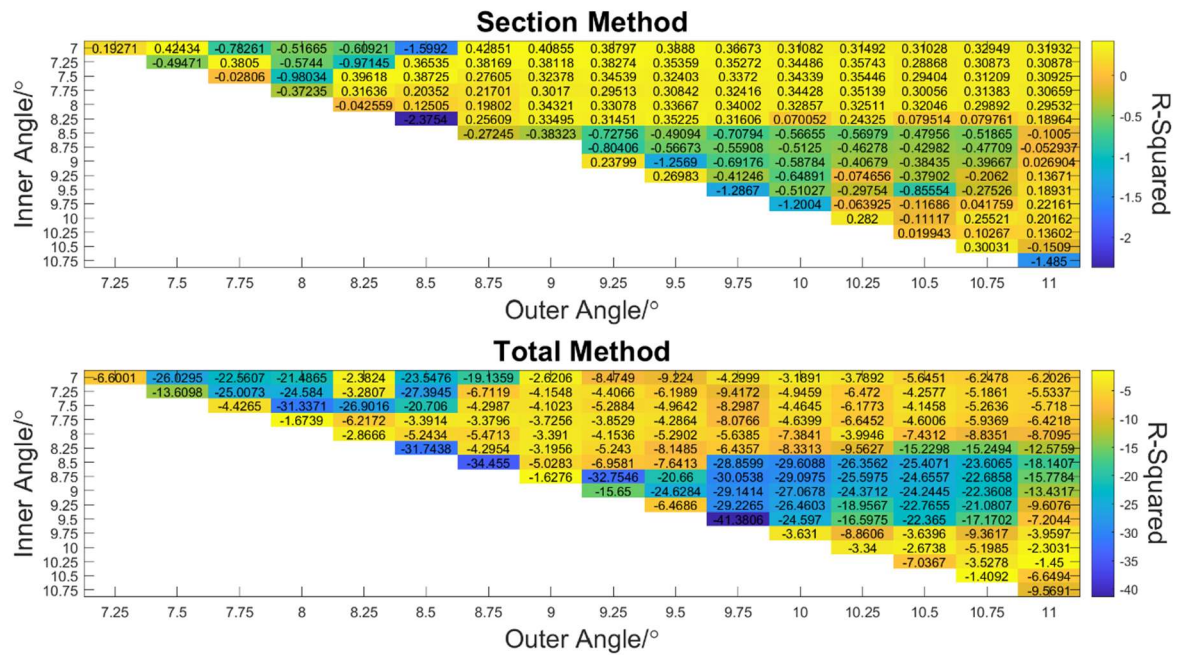


Figure 7.18: R-squared values for the gradient diameter measurement results compared to a function of $y = x$ for data modelled in GLMT. The top shows the results using the section method, the bottom shows the results using the total method. The y-axis indicates the smaller angular limit, closer to the forward scattering direction, the x-axis indicates the larger angular limit.

7.6 Extra Image Analysis

In addition to the example scattering, measurement, and remodelling shown in Section 5.4.3.3, examples of different fibre diameters and lengths are shown in Figure 7.19, Figure 7.20, and Figure 7.21.

PPD2 Captured Scattering Data Comparison with a
0.7 μm Diameter by 3.5 μm Long Cylinder Modelled in ADDA

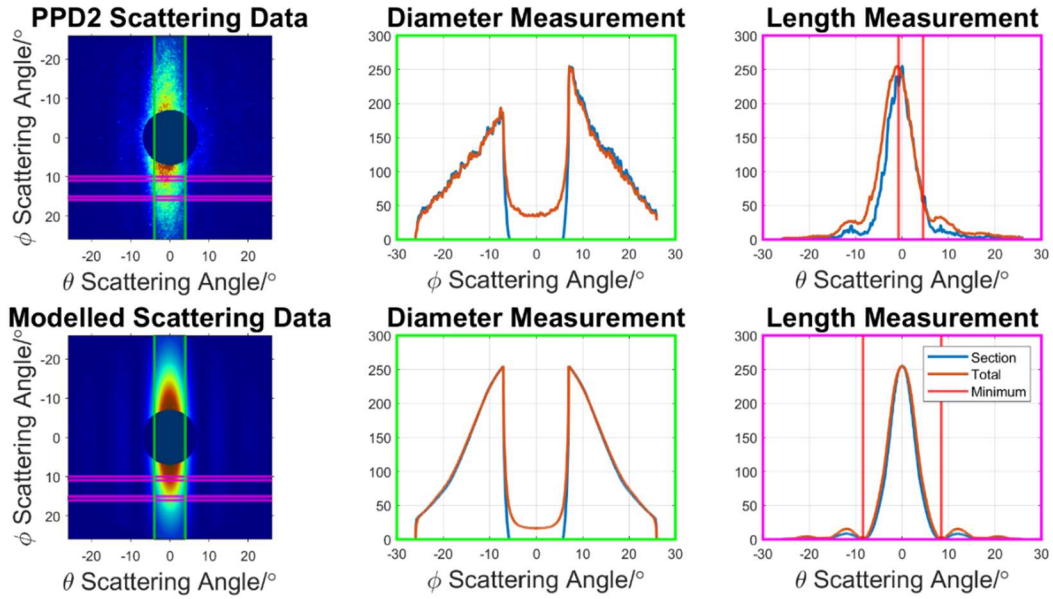


Figure 7.19: PPD2 scattering data (top row) showing the forward scattering image with marked sections (left), the scattering data used for the diameter measurements (middle), and the scattering data used for the length measurements (right). The red vertical lines indicate the minimum. The bottom row shows the same analysis of the scattering modelled by ADDA of a 0.7 μm diameter by 3.5 μm long cylinder that were the dimensions obtained from the top row.

PPD2 Captured Scattering Data Comparison with a
1.8 μm Diameter by 11 μm Long Cylinder Modelled in ADDA

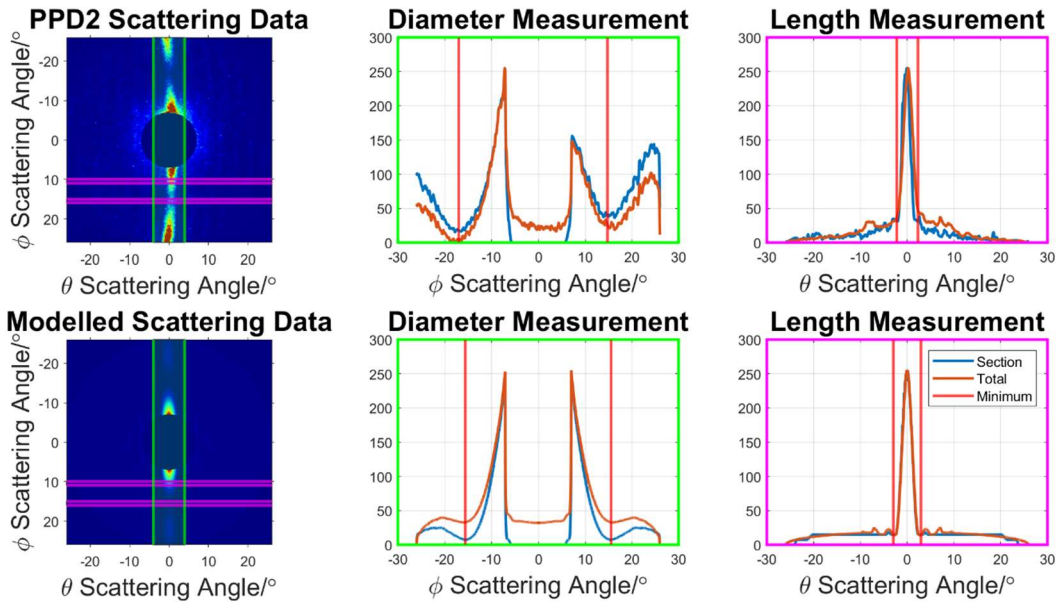


Figure 7.20: PPD2 scattering data (top row) showing the forward scattering image with marked sections (left), the scattering data used for the diameter measurements (middle), and the scattering data used for the length measurements (right). The red vertical lines indicate the minimum. The bottom row shows the same analysis of the scattering modelled by ADDA of a 1.8 μm diameter by 11 μm long cylinder that were the dimensions obtained from the top row.

PPD2 Captured Scattering Data Comparison with a
0.75 μm Diameter by 10 μm Long Cylinder Modelled in ADDA

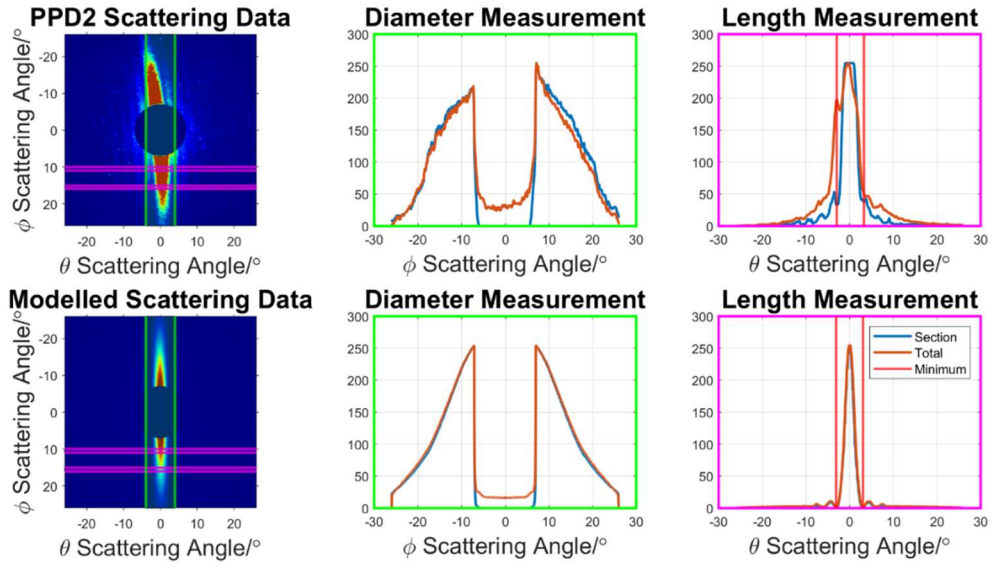


Figure 7.21: PPD2 scattering data (top row) showing the forward scattering image with marked sections (left), the scattering data used for the diameter measurements (middle), and the scattering data used for the length measurements (right). The red vertical lines indicate the minimum. The bottom row shows the same analysis of the scattering modelled by ADDA of a 0.75 μm diameter by 10 μm long cylinder that were the dimensions obtained from the top row.