Complex Permittivity and Scattering Characteristics of Forest Fire Ash Particles at Microwave and Millimetre Wave Frequencies

A dissertation submitted in fulfilment of the requirement for the degree of
Doctor of Philosophy

Thomas C. Baum
Bachelor of Engineering – Aerospace (Hons.)

School of Electrical and Computer Engineering (SECE)
School of Aerospace, Mechanical and Manufacturing Engineering (SAMME)
College of Science, Engineering and Health
RMIT University

May 2014
Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the dissertation is the result of work which has been carried out since the official commencement date of the approved research program.

Thomas C. Baum

14-April-2014
Acknowledgements

The work carried out for this project would not have been possible without the input from both my supervisors Prof. Kamran Ghorbani and AProf. Lachlan Thompson. They gave me the freedom to explore a number of different avenues to help shed light on this difficult problem, whilst sharing their vast experience and knowledge where needed. I would also like to acknowledge Mr. David Welch as a most talented technical staff member, who helped greatly in fixing test equipment and building experimental setups when requested, along with the wise Mr. Alex Zylewicz. I would like to acknowledge RMIT University for allowing me to smoke out the building on numerous occasions and for providing a number of excellent testing facilities that would have otherwise made the project impossible to complete. This is especially true for the RMIT Microscopy and Microanalysis Facility headed by Mr. Phil Fransis.

Personally, I would like to acknowledge my parents Gregory and Gabriella Baum for their support in the project. They provided farmland used for trilling RMIT X-Band Radar for testing. Also, thanks to Russell and Sandra Duncombe for allowing the team to set up radar hardware on their property.

Finally, I would like to acknowledge my partner Miss. Sophia Katos who has been a great source of encouragement and who has graciously spent a large amount of time proof reading all my conference and journal publications, as well as this dissertation.
Abstract

The geometric, physical, dynamic and scattering properties of ash particulates resulting from Australian biomass, along with the complex permittivity, have been presented within this dissertation. The rationale behind this work relates to the characterisation of the fundamental scattering properties of ash particulates, with the primary goals being to aid active radar system design and to provide a basic framework for a complex inverse scattering model.

The reflectivity coefficient for a volumetrically dispersed medium has been defined by characterising three distinct properties of ash. Firstly, statistical modelling of ash created from various plant and tree species was conducted in order to describe its geometric and material behaviour. Here, similarities between plant and tree species with comparable foliage were noted. Three probability distribution functions (PDF) relating to the projected area, aspect ratio and through thickness dimensions for large ash particles (>0.2mm²) have been mapped. Material investigation has included analysis of the effects of temperature on biomass and the resultant geometric changes this incurs. Furthermore, the effects of natural moisture absorption rates and porosity estimations using measured and micro-computer-tomography (Micro-CT) techniques have been presented.

An analysis of the dynamic behaviour of ash particles within a defined volume of space displaying different modes provides the second area of investigation. Particular focus has been given to the ascent and descent phases of the ash particles, with analysis of three dynamic stability modes; namely tumbling, fluttering and chaotic random. Probability distribution functions for orientation and analysis of velocities and Reynolds numbers have been established using video processing techniques.

The complex permittivity of ash at both low and high temperatures has been measured. Here, an empirically derived mixing law has been established to theoretically model the complex permittivity of ash. This model also takes into account concentrations of water that may be absorbed by the highly porous material.

By applying the knowledge gained from the analysis of ash particles, extensive modelling and measurement work has been carried out to determine their reflectivity. Simulated modelling of the ash has been achieved using a hybrid simulation scheme to accurately implement statistical models over a wide range of frequencies (1-40GHz).
Contents

Declaration ............................................................................................................................................ i
Acknowledgements ................................................................................................................................ ii
Abstract ................................................................................................................................................ iii
Contents ................................................................................................................................................ iv
List of Figures ........................................................................................................................................ v
List of Tables ......................................................................................................................................... xvii
Glossary ................................................................................................................................................ xix
Chapter 1 – Introduction .................................................................................................................... 1
  1.1 Introduction ................................................................................................................................ 1
  1.2 Radar, Radar Cross-Section, Frequencies and Ash ....................................................................... 2
  1.3 Motivation .................................................................................................................................... 4
    1.3.1 Thesis Overview .................................................................................................................... 5
  1.4 List of Publications ....................................................................................................................... 7
    1.4.1 Peer-Reviewed Journal Articles ............................................................................................. 7
    1.4.2 Peer-Reviewed Conference Proceedings .................................................................................. 8
  1.5 Original Contributions .................................................................................................................. 9
Chapter 2 - Literature Review .......................................................................................................... 10
  2.1 Introduction ................................................................................................................................ 10
  2.2 Forest Fire Remote Sensing .......................................................................................................... 10
  2.3 Radars Observing Fire .................................................................................................................. 12
  2.4 Australian Examples of Radar Observation of Forest Fires ........................................................... 16
  2.5 Research Questions and Methodology ......................................................................................... 27
    2.5.1 Research Questions ............................................................................................................... 27
    2.5.2 Methodology for Research .................................................................................................... 29
  2.6 Conclusion .................................................................................................................................... 32
Chapter 3 – Geometric and Dynamic Properties of Ash ................................................................. 33
  3.1 Introduction ................................................................................................................................ 33
  3.2 Tree/Plant Species Samples ......................................................................................................... 34
    3.2.1 Eucalyptus Genus ................................................................................................................... 35
3.2.2 Acacia Genus....................................................................................................................37
3.3 Origins of Ash..........................................................................................................................39
3.3.1 Properties of fires.............................................................................................................39
3.4 Image Processing Results for Open Fire Tests .....................................................................52
3.5 Alternative Methods for Creating Ash..................................................................................54
3.6 Geometric Properties of Ash Particles ..................................................................................61
3.6.1 Particle Projected Area Distributions................................................................................61
3.6.2 Particle Aspect Ratio Distributions....................................................................................63
3.6.3 Particle Thickness/Cross-Section Distributions.................................................................65
3.6.4 Particle Geometry Relative to Tree/Plant Species (Shape Type). .......................................69
3.6.5 Surface and Through Thickness Geometry......................................................................79
3.6.6 Summary of PDF Functions for Ash..................................................................................82
3.7 Physical Material Properties of Biomass and Ash.................................................................84
3.7.1 Effects of Temperature on Organic Materials ....................................................................84
3.7.2 SEM-EDX Elemental Analysis..........................................................................................88
3.7.3 Moisture Absorption Rates ............................................................................................92
3.7.4 Porosity, Density and Cell Structure with Respect to Temperature.................................95
3.8 Ash Particle Dynamics..........................................................................................................103
3.8.1 Dynamics of Fires – Thermal and Fluidic .........................................................................103
3.8.2 Particle Dynamics in Ascent and Descent Phase..............................................................106
3.9 Conclusion................................................................................................................................112

Chapter 4 – Complex Permittivity of Ash Particles..................................................................114
4.1 Introduction............................................................................................................................114
4.2 VNA TRL Calibration ..........................................................................................................117
4.2.1 Unified Mixing Law.........................................................................................................120
4.3 Effective Relative complex permittivity of Ash Created in Uncontrolled Fires Conditions...123
4.3.1 Fitted Dielectric Mixing Law Models for Uncontrolled Samples.................................131
4.3.2 Effects of Particle Geometry on the Unified Mixing Law ................................................137
4.4 Relative Complex Permittivity of Controlled Ash at Low Temperatures (≤ 400 °C).........141
4.4.1 Sample Preparation .........................................................................................................142
4.4.2 Relative Complex Permittivity at X-Band (8 – 12 GHz) and Ka-Band (26.5 – 40 GHz)...145
4.5 Relative Complex Permittivity of Controlled Ash at High Temperatures (> 400 °C).......152
4.5.1 Unified Mixing Law Semi-Empirical Modelling of Powdered Ash at X-Band and Ka-Band
..............................................................................................................................153
4.6 Micro Computer Tomography EM Simulations ................................................................. 159
4.7 A Generalised Fitted Relative Complex Permittivity Model for Ash............................ 165
  4.7.1 Generalised Relative Complex Permittivity with Moisture Inclusion .................... 169
4.8 Conclusion .................................................................................................................. 178
Chapter 5 – Radar Cross-Section and Simulated Reflectivity ............................................. 181
  5.1 Introduction .............................................................................................................. 181
  5.2 Radar Cross-Section (RCS) Measurements of an Ash Particle............................... 182
    5.2.1 Wideband Simulated Mono-Static 2D Radar Cross-Section of Dielectric Disks .... 192
    5.2.2 Wideband Simulated Mono-Static 2D Radar Cross-Section of an Arbitrary Shaped
        Dielectric Planar Ash Particles .............................................................................. 197
    5.2.3 Wideband Simulated Mono-Static RCS of Multi-Dielectric Planar Ash Particle ..... 201
  5.3 Relative Complex Permittivity Distribution of Ash Created from Fires .................... 206
    5.3.1 Coupling between Particle Projected Area and Effective Exposed Temperature .... 212
  5.4 Ash Reflectivity ...................................................................................................... 216
    5.4.1 Measurements of Reflectivity of Eucalypt Disks ................................................ 217
  5.5 Reflectivity Simulations .......................................................................................... 225
    5.5.1 Simulation Framework ...................................................................................... 226
    5.5.2 Simulated Reflectivity Results .......................................................................... 230
  5.6 Conclusion .............................................................................................................. 236
Chapter 6 - Conclusion and Future Work .......................................................................... 238
  6.1 Conclusions ............................................................................................................. 238
    6.1.1 Geometric and Dynamic Properties of Ash ....................................................... 238
    6.1.2 Complex Permittivity of Ash Particles .............................................................. 239
    6.1.3 Radar Cross-Section and Simulated Reflectivity .............................................. 240
  6.2 Future Work and Concluding Remarks .................................................................... 242
    6.2.1 Further Investigation on the Complex Permittivity of Ash ................................. 243
    6.2.2 Permittivity Distribution from Bushfires ............................................................ 243
    6.2.3 Particle Concentration ...................................................................................... 243
    6.2.4 Validation of Scattering Models ........................................................................ 244
    6.2.5 Investigation of Other Scattering Sources ......................................................... 244
APPENDIX ....................................................................................................................... 245
A.  Review of Electromagnetics and Radar Fundamentals ................................................ 245
    Interaction of Electromagnetic Fields within Mediums ............................................. 245
    Radar Fundamentals ............................................................................................... 248
Theoretical Kirchhoff Wideband Mono-Static 2D Radar Cross-Section of Ash Particles ..........................................................253
Probability Distribution Functions (PDF) ..................................................................................................................256
Extended Debye Model for Water to 100 GHz with temperature dependency .........................................................257

B. Tree and Plant Species ..............................................................................................................................................259
   Eucalyptus Genus ......................................................................................................................................................259
   Acacia Genus ............................................................................................................................................................262
   Pteridium Genus ........................................................................................................................................................263
   Casuarina Genus ........................................................................................................................................................264
   Pinus Genus ..............................................................................................................................................................265
   Cupressus Genus ......................................................................................................................................................266

C. Image Processing Techniques ..................................................................................................................................267
   Image Normalisation Process ..................................................................................................................................270
   Image Processing Technique for Maximum Expose Temperature ..............................................................................271

D. Normalised Mean RGB and LAB models ..................................................................................................................276
   Eucalypt Genus ..........................................................................................................................................................277
   Acacia Genus ............................................................................................................................................................281
   Pteridium Genus ........................................................................................................................................................283
   Pinus Genus ..............................................................................................................................................................284

E. Codes ...........................................................................................................................................................................286
   Image Normalisation Macro for ImageJ ......................................................................................................................286

REFERENCES .................................................................................................................................................................287
List of Figures

Fig. 1 – Example of equivalent rainfall rate for the black Saturday fires 7th February 2009 as taken by a Selex-Gematronik M1500-S1, S-band Doppler weather radar - Australian Bureau of Meteorology © ................................. 18

Fig. 2 – Example of wind speed rate for the black Saturday fires 7th February 2009 as taken by a Selex-Gematronik M1500-S1, S-band Doppler weather radar - Australian Bureau of Meteorology © ............................... 19

Fig. 3 – Composite image of the Black Saturday fires taken using 250m MODIS on NASA’s AQUA satellite and the equivalent Australian Bureau of Meteorology © Melbourne Airport radar scan at 4:50 UTC (3:50pm AEDT) on the 2-Feb-2009, Image courtesy of NASA[95] and Australian Bureau of Meteorology © .......................... 21

Fig. 4 – Composite image of the Anglesea basin controlled burn taken using 250m MODIS on NASA’s AQUA satellite at 4:50 UTC (3:50pm AEDT) and the equivalent Australian Bureau of Meteorology © Melbourne Laverton Selex-Gematronik M1500-S1, S-band Doppler weather radar scan at 4:54 UTC (3:54pm AEDT) on the 28th March 2009, Image courtesy of NASA[96] and Australian Bureau of Meteorology © ............................ 23

Fig. 5 – (Top) Photo taken from Urquhart’s Bluff at 3:30pm AEST of the Anglesea basin fire on the 28-Mar-2009, the image showing the extent of the solid particulates ejected into the atmosphere by the thermodynamic cycle of the fires and the lack of pyro-cumulonimbus formations above the fire. (Middle) Typical Biomass consumed during the fire. (bottom) Aftermath of the Anglesea basin fire ............................................................... 24

Fig. 6 – Composite image of the Hotham Heights and Lake Thomson fires taken using 250m MODIS on NASA’s AQUA satellite at 4:50 UTC (3:50pm AEDT) and the equivalent Australian Bureau of Meteorology © scan at 4:50 UTC (3:50pm AEDT) from the Yarawonga WSR-81C, C-Band Doppler weather radar shows the reflectivity of the Hotham Heights fires while the Lake Thomson fires reflectivity is that from the 4:54 UTC (3:54pm AEDT) scan from the Melbourne Laverton Selex-Gematronik M1500-S1, S-band Doppler weather radar. Both scans taken on the 24th January 2013, Image courtesy of NASA[97] and Australian Bureau of Meteorology © ................................................................. 26

Fig. 7 – Graphical representation of the total radar cross-section containing the contributions of the volumetric radar cross-section of each particle contained within a resolute scattering volume ........................................ 29

Fig. 8 – Roadmap for understanding the scattering characteristics of solid ash particulates .............................................. 30

Fig. 9 – Graphical representation of the different geometric, dynamic and electromagnetic properties required to characterise the radar cross-section of an individual ash particle. Included is the relative chapters and section where these properties have been analysed........................................................................ 31

Fig. 10 – Map of Australia showing the population of the Eucalyptus genus (blue dots) [106, 109] .................. 35

Fig. 11 – Geographical map of Australia showing the population of the Messmate Eucalypt (blue dots) [106, 109] ................................. 36

Fig. 12 – Geographical map of Australia showing the population of the Acacia Genus (blue dots) [106, 109] 37

Fig. 13 – Geographical map of Australia showing the population of the Blackwood Wattle (blue dots) [106, 109] ................................................................................................................. 38
Fig. 14 – Illustration of the experimental setup use for measuring the temperature of small open fires using eucalypt biomass.

Fig. 15 – Temperature profile of a 0.5 m x 0.5 m fire with a fuel loading factor of 1 kg/m².

Fig. 16 – Temperature profile of a 0.5 m x 0.5 m fire with a fuel loading factor of 2 kg/m².

Fig. 17 – Temperature profile of a 0.5 m x 0.5 m fire with a fuel loading factor of 3 kg/m².

Fig. 18 – Example of the open fire test with Fl = 3

Fig. 19 – Results of the ash generated from the open fire test with Fl = 3

Fig. 20 – Results of the ash generated from the open fire test with Fl = 2

Fig. 21 – Rendered illustrations of the open fire particle collection frame. Side view illustrates the thermodynamic principle of how the particles are lifted into the atmosphere then fall out onto the collection frame.

Fig. 22 – Small open fire test with particle capture frame. a) heaped eucalyptus biomass in centre of frame, b) Heap size relative to 30cm ruler, c) initial burning with particle on collection frame, d) illustration of embers being ejected from fire, e) completion of the open fire test and f) example of the remaining ash.

Fig. 23 – Illustrations of the variability of particle collected on the frame of the open fire tests. Particles then taken and image processed to work out geometric distributions.

Fig. 24 – Examples of large flying ash deposited up to 2m away from the collection frame of the open fire tests.

Fig. 25 – Projected surface area of 4133 particles collected from a number of the open fire tests. Results analysed using Image processing. Distribution fitted with a generalized pareto PDF with k = -0.38, σ = 1.50, θ = 0.

Fig. 26 – Aspect ratio of 4133 particles collected from a number of the open fire tests. Results analysed using Image processing. Distribution fitted with a generalized extreme value (GEV) PDF with k = -0.335, σ = 0.19, μ = 0.489.

Fig. 27 – 3D illustration of the burn chamber developed for generating ash particles.

Fig. 28 – Measured and 3D interpolated linear velocity (m/s) along the axial length of the burn chamber, shown is slices of the velocity at a) 25 mm, b) 100 mm and c) 185 mm in the Z-dimension. Colour bar correlates measured wind speed within the chamber (m/s).

Fig. 29 – Examples of a) the types of biomass placed inside the burn chamber, b) the resultant ash caught on mesh screens and c) scanned images of ash particles pre-processed to remove background information and noise.

Fig. 30 – Flame temperature measurements form thermocouples within the burn chamber based on a fuel loading factor of Fl = 1. Max air velocity ($V_{ave} = 1.44$ m/s), Atm.Temp. 22 °C, RH = 35%.

Fig. 31 – Flame temperature measurements form thermocouples within the burn chamber based on a fuel loading factor of Fl = 2. Max air velocity ($V_{ave} = 1.44$ m/s), Atm.Temp. 23 °C, RH = 37%.
Fig. 32 – Flame temperature measurements from thermocouples within the burn chamber based on a fuel loading factor of $f_i = 4$. Max air velocity ($V_{ave} = 1.44$ m/s), Atm.Temp. 21 °C, RH = 37%.

Fig. 33 – Projected area distributions for messmate eucalypt ash particles $\geq 0.20\text{mm}^2$ with a fitted generalized pareto distribution $k = 0.7215$, $\sigma = 1.1326$, $\theta = 0$.

Fig. 34 – Projected area distributions for blackwood wattle ash particles $\geq 0.20\text{mm}^2$ with a fitted generalized pareto distribution $k = 0.5063$, $\sigma = 0.7832$, $\theta = 0$.

Fig. 35 – Aspect ratio distribution for messmate eucalypt ash with fitted generalized extreme value distribution $k = -0.4175$, $\sigma = 0.1957$, $\mu = 0.543$.

Fig. 36 – Aspect ratio distribution for blackwood wattle ash with fitted generalized extreme value distribution $k = -0.3758$, $\sigma = 0.1893$, $\mu = 0.5238$.

Fig. 37 – Micro-CT scans illustrating changes to the cross sectional thickness of messmate eucalypt leaves exposed to temperatures (from top to bottom): a) dry, b) 150 °C, c) 200 °C, d) 250 °C, e) 300 °C, f) 350 °C, g) 400 °C. NOTE: Each image is a CT-scan taken from a different leaf structure.

Fig. 38 – Changes in the projected area of messmate eucalypt leaves exposed to temperatures (from left to right): a) dry, b) 150°C, c) 200°C, d) 250°C, e) 300°C, f) 350°C, g) 400°C. All samples were originally punched into 6.1mm disk, then exposed to each temperature range on a hotplate.

Fig. 39 – Reduction in the projected area of eucalypt biomass at various temperatures. Reduction in area follows a similar trend to the normalised mass loss of the eucalypt species.

Fig. 40 – Thickness distribution for Messmate Eucalypt ash with fitted normal distribution, $\sigma = 0.0394$, $\mu = 0.2668$.

Fig. 41 – Thickness distribution for Blackwood wattle ash with fitted normal distribution, $\sigma = 0.0804$, $\mu = 0.3036$.

Fig. 42 – Examples of a) under side of the bracken fern foliage, b) cell structure of a messmate eucalypt branch and c) external shape of a dried cypress needle.

Fig. 43 – Examples of large messmate eucalypt ash particles showing their planar type geometries.

Fig. 44 – Examples of large blackwood wattle ash particles showing their planar type geometries.

Fig. 45 – Examples of large bracken fern ash particles showing their planar type geometries.

Fig. 46 – Examples of large Sheoak ash particles showing their needle type geometries.

Fig. 47 – Examples of large Sheoak ash particles showing their needle type geometries.

Fig. 48 – Examples of large laylandii cypress ash particles showing their needle type geometries.

Fig. 49 – SEM image of typical small ash particles created from the a high temperature eucalypt sample (1000-1100 °C).

Fig. 50 – SEM image of typical small ash particles created from the a moderate temperature blackwood wattle sample (800-900 °C).
Fig. 51 – SEM image of typical small ash particles created from the a moderate temperature bracken fern sample (800-900 °C)

Fig. 52 – SEM image of typical small ash particles created from the a moderate temperature sheoak sample (800-900 °C)

Fig. 53 – SEM image of typical small ash particles created from the a moderate temperature radiate pine sample (800-900 °C)

Fig. 54 – SEM image of typical small ash particles created from the a moderate temperature cypress sample (800-900 °C)

Fig. 55 – Cross-sectional and surface SEM scans of a) messmate Eucalypt leaf, b) blackwood wattle leaf, c) radiata pine needle, d) Bracken fern leaf and e) Sheoak needle respectively

Fig. 56 – Time required for messmate eucalyptus leaves to stabilise in mass when exposed to different temperatures

Fig. 57 – Normalised mass loss of different biomass up to 400 °C. MM- Messmate Eucalypt, SG – Spotted Gum, IB – Iron Bark, BW – Blackwood Wattle, m - measured data and f- fitted cubic extrapolation

Fig. 58 – Normalised mass loss of the messmate eucalypt biomass over various temperature ranges

Fig. 59 – SEM-EDX measurement of the concentration by weight and elemental breakdown of messmate eucalypts leaves versus temperature

Fig. 60 – SEM-EDX measurement of the concentration by weight and elemental breakdown of blackwood wattle leaves versus temperature

Fig. 61 – Measured absorption rates of atmospheric moisture for Eucalypt biomass at various temperatures. (atm. temp = 22.5°C, RH = 35.5%)

Fig. 62 – Time sequence demonstrating the rapid absorption of ash into a water droplet from capillary effects. (atm. temp. = 22°C, RH = 40%)

Fig. 63 – Measured bulk density of messmate eucalypt leaves at up to 400 °C, model extended based on normalised mass loss curve from Fig. 58

Fig. 64 – Measured bulk density of Blackwood wattle leaves at up to 400 °C. Comparison of measured values against the average bulk density of the messmate eucalypt is shown by the dotted line

Fig. 65 – Porosity extraction using MicroCT at 2.18 μm voxel resolution

Fig. 66 – Micro CT cross-section slices of messmate eucalypt leaves exposed to temperatures of a) unburnt, b) 150°C, c) 200°C, d) 250°C, e) 300°C, e) 350°C and f) 400°C. (scale bar represents a total length of 1500 μm). (Measurements of messmate leaf samples courtesy of Dr. Benedicta Arhatari, Department of Physics, Latrobe University) Prepared at RMIT University

Fig. 67 – Illustration of a single horizontal vortex, blue arrows represents air vectors forming the vortex and red arrows represent ambient wind condition and direction of fire

Fig. 68 – Illustration of a horizontal vortex pairs, blue arrows represents air vectors forming the vortex and red arrows represent ambient wind condition and direction of fire
Fig. 69 – Illustration of a transverse vortex, blue arrows represents air vectors forming the vortex, green represent the air vector forming a ring shape and red arrows represent ambient wind condition and direction of fire.

Fig. 70 – Illustration of a vertical roll vortex, blue arrows represents air vectors forming the vortex and red arrows represent ambient wind condition and direction of fire.

Fig. 71 – Measured trajectory plots for a number of messmate eucalyptus ash particles showing the development of both the fluttering and tumbling modes in the descent phases, and stable chaotic mode during the ascent phase. Each horizontal bar represents the semi-major axis of each particle and a time step of approximately 8ms. T = Tumbling, F = Fluttering, C = Stable Chaotic, A = Ascent and D = Descent.

Fig. 72 – Messmate eucalypt ash particle orientation PDF from the horizontal plane with fitted normal distribution, µ = 0, σ = 31.98. Data extracted from high speed video.

Fig. 73 – Measured trajectory plots for a number of radiata pine ash particles showing the development of only the fluttering modes in the descent phases, and stable chaotic mode during the ascent phase. Each horizontal bar represents the semi-major axis of each particle and a time step of approximately 8ms. F = Fluttering, C = Stable Chaotic, A = Ascent and D = Descent.

Fig. 74 – Radiata pine ash particle orientation PDF from the horizontal plane with fitted normal distribution, µ = 0, σ = 35.84. Data extracted from high speed video.

Fig. 75 – Typical sample holding arrangements for a) coaxial and b) waveguide T/R measurement for the extraction of S-parameters for determining a MUT’s relative complex permittivity and permeability. Coaxial samples are approximately 7mm in outer diameter while waveguide samples must fill the respective waveguide short and board wall dimensions.

Fig. 76 – VNA 8-term forward error calibration model used in a TRL calibration.

Fig. 77 – Waveguide LRL/TRL calibration setup and 5mm sample holder overview.

Fig. 78 – Flow chart demonstrating the measurement procedure used to measure samples using the NRW method. Most samples were tested more than three times over a number of different days to confirm repeatability of measurements.

Fig. 79 – Real (solid line) and imaginary components (dashed line) of the complex permeability and permittivity of a 0.125” Rogers Duroid 5880 substrate. Substrate measurement was used as a standard for determining measurement setup error.

Fig. 80 – Ash samples used in dielectric constant measurement in order of light to darks, a) Eucalypt, b) Cypress, c) Bracken Fern, d) Sheoak, e) Wattle.

Fig. 81 – Real (solid line) and imaginary components (dashed line) of the complex permeability and permittivity of a dry and wet eucalypt sample. Wet real and imaginary components are represented by the upper solid and dashed line while the dry real and imaginary components are represented by the lower solid and dashed lines. Samples measured at 22.8°C with water concentration of 30% w/w.

Fig. 82 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a Wattle Tree sample at 22.8°C.
Fig. 83 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a bracken fern sample at 22.8ºC. 
Fig. 84 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a sheoak sample at 22.8ºC.
Fig. 85 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a Radiata Pine sample at 22.8ºC.
Fig. 86 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a Cypress Tree sample at 22.8ºC.
Fig. 87 – Measured ('M') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for dry eucalypt ash. Optimal when $v = 10.10$
Fig. 88 – Measured ('M') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for dry wattle tree ash. Optimal when $v = 10.60$
Fig. 89 – Measured ('M') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for dry bracken fern ash. Optimal when $v = 9.95$
Fig. 90 – Measured ('M') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for dry sheoak ash. Optimal when $v = 10.06$
Fig. 91 – Measured ('M') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for un-dried pine ash. Optimal when $v = 10.40$
Fig. 92 – Measured ('M') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for dry cypress ash. Optimal when $v = 9.99$
Fig. 93 – Simulated ('S') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for random spheres 0.5-1.0mm diameter. $\varepsilon_i = 10+0.2i$, resultant depolarization factor $v=1.5$
Fig. 94 – Simulated ('S') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for random spheres 1.0-1.5mm diameter. $\varepsilon_i = 10+0.2i$, resultant depolarization factor $v=2$
Fig. 95 – Simulated ('S') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for random plates of thickness 0.1mm at 0.5-1.0mm (LxW). $\varepsilon_i = 10+0.2i$, resultant depolarization factor $v=75$
Fig. 96 – Simulated ('S') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity for random plates of thickness 0.1mm at 1.0-1.5mm (LxW). $\varepsilon_i = 10+0.2i$, resultant depolarization factor $v=14$
Fig. 97 – Waveguide sample holder used to ensure ash samples are held perpendicular to a propagating electromagnetic filed. a) exploded view of holder, b) assembles holder, c) 0.25mm gap in the length and width of the shim waveguide dimensions and d) placement of ash in the waveguide shim
Fig. 98 – Examples of messmate eucalypt leaves collected, dried/pressed and exposed at various temperature ranges.
Fig. 99 – Box-plot of dielectric constant and loss tangent for messmate eucalypt leaves exposed to various
temperatures. X-Band mid-band response at 10GHz, Ambient Temp 22°C, RH 42%.

Fig. 100 – Box-plot of dielectric constant and loss tangent for blackwood wattle leaves exposed to various
temperatures. X-Band mid-band response at 10GHz, Ambient Temp 23°C, RH 49%.

Fig. 101 – Box-plot of dielectric constant and loss tangent for spotted gum leaves exposed to various
temperatures, X-Band mid-band response at 10GHz, Ambient Temp 22°C, RH 34%.

Fig. 102 – Box-plot of dielectric constant and loss tangent for iron bark eucalypt leaves exposed to various
temperatures, X-Band mid-band response at 10GHz, average ambient measure temp. 22°C, RH 35%.

Fig. 103 – Box-plot of dielectric constant and loss tangent for messmate eucalypt leaves exposed to various
temperatures, Ka-Band response at 38GHz, average ambient measure temp. 21°C, RH 35%.

Fig. 104 – Effective permittivity vs. bulk density for various ash samples. Average ambient measure temp. 23°C, RH 45%.

Fig. 105 – Loss tangent vs. bulk density for various ash samples. Average ambient measure temp. 23°C, RH 45%.

Fig. 106 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the
relative permittivity of messmate eucalypt ash exposed at 450°C (10GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 107 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the
relative permittivity of messmate eucalypt ash exposed at 500°C (10GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 108 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the
relative permittivity of messmate eucalypt ash exposed at 1000°C (10GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 109 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the
relative permittivity of messmate eucalypt ash exposed at 450°C (38GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 110 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the
relative permittivity of Blackwood wattle ash exposed at 450°C (10GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 111 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the
relative permittivity of Blackwood wattle ash exposed at 500°C (10GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 112 – Example of a MicroCT 3D model of messmate eucalypt ash. (Measurements of messmate samples
courtesy of Dr. Benedicta Arhatari, Department of Physics, Latrobe University)

Fig. 113 – Measured permittivity and loss tangent for the messmate eucalypt samples

Fig. 114 – Inclusion/solid permittivity and loss tangent of ash predicted form the back optimization process
carried out in CST MWS.
Fig. 115 – Optimization matching error

Fig. 116 – Permittivity and loss tangent predicted from using the unified mixing law.

Fig. 117 – Corrected loss tangent predicted from using the unified mixing law.

Fig. 118 – Debye dispersive model for water where $\varepsilon_s = 78.4$, $\bar{\varepsilon}$ = 3.1 and $\tau = 8.27 \times 10^{-3}$ ns (at 25 °C).

Fig. 119 – Measurement of the effective complex permittivity of powdered ash with respect to different moisture contents by weight. Bulk density of dry ash sample within waveguide holder was $\sigma_{\text{bulk}}$ = 0.895 g/cm$^3$ (atm. temp = 21.5°C, RH = 37.5%).

Fig. 120 – Performance of the substituted unified mixing law with respect to measured and predicted permittivity. $\varepsilon_a$ is measured high volume fraction data, $\varepsilon_b$ is measured low volume fraction data, $\varepsilon_w$ is the relative complex permittivity of water under various conditions and $v$ is the depolarisation factor where $v(f)_{\text{emp}}$ is an empirically derived regression curve.

Fig. 121 – Permittivity and loss tangent predicted from the substituted unified mixing law for ash at various exposed temperature and moisture contents. Analysis taken for a case at 10GHz, 21.5°C.

Fig. 122 – Permittivity and loss tangent predicted from the substituted unified mixing law for ash at various exposed temperature and moisture contents. Analysis taken for a case at 38GHz, 21.5°C assuming the change in permittivity between X-band and Ka-Band are neglected.

Fig. 123 – Power density inside a WR-90 waveguide at the mid-band frequency of 10GHz. Simulated using CST Microwave Studio.

Fig. 124 – Waveguide RCS measurements setup showing a) sample holder with calibration standard in waveguide HP matched terminations, b) Assembled waveguide RCS setup and c) mounting of the medium (M) and large(L) disks in waveguide. Axis systems for RCS measurements also illustrated with respect to incident field (E) angles ($\theta$ and $\phi$).

Fig. 125 – Measured RCS of L-Disks of messmate eucalypt ash at various temperatures. Samples of starting diameter $d \sim 7$ mm. Image of exposed disks illustrated at top (from left to right 22 °C to 500 °C).

Fig. 126 – Measured RCS of M-Disks of messmate eucalypt ash at various temperatures. Samples of diameter $d = 5$ mm.

Fig. 127 – Simulated RCS of L-Disks of messmate eucalypt ash at various temperatures. Samples of starting diameter $d \sim 7$ mm.

Fig. 128 – Simulated RCS of M-Disks of messmate eucalypt ash at various temperatures. Samples of starting diameter $d \sim 4.7$ mm.

Fig. 129 – Simulated 2D mono-static RCS ($\sigma_{\text{hh}}$) of the L-Disks of messmate eucalypt ash with the geometric and RF properties outlined in Table 19 with respect to frequency. a) 150 °C, b) 200 °C, c) 250 °C, d) 300 °C, e) 350 °C, f) 400°C, g) 441 °C, and h) 500 °C.

Fig. 130 – Simulated 2D horizontally polarised mono-static RCS ($\sigma_{\text{hh}}$) of a messmate eucalypt ash particle with an effective exposed temperature of 441 °C ($\varepsilon = 1.15$). Particle represented as a disk with various cross-sectional diameters of a) 1mm, b) 3mm, c) 5mm and d) 7mm showing the formation of the first null at higher frequencies.
Fig. 131 – Simulated 2D vertically polarised mono-static RCS ($\sigma_{vv}$) of a messmate eucalypt ash particle with an effective exposed temperature of 441 °C ($\varepsilon = 1.15$). Particle represented as a disk with various cross-sectional diameters of a) 1mm, b) 3mm, c) 5mm and d) 7mm showing the formation of the first null at higher frequencies.

Fig. 132 – Illustration of the two chosen large ash particle with an approximated effective exposed temperature and projected area of a) Temp = 408.5 °C, $A = 44.64 \text{ mm}^2$ and b) Eff. Temp = 489.5 °C, $A = 42.63 \text{ mm}^2$.

Fig. 133 – Coordinate system used to analysed the 2D RCS of the two arbitrary ash particle.

Fig. 134 – Equivalent colour of the each ash particle. The effective temperature and approximated relative complex permittivity using $\text{dE}^{00}$ colour matching for a) Eff. Temp = 408.5 °C, $\varepsilon_r = 1.55$ and b) Eff. Temp = 489.5 °C, $\varepsilon_r = 1.065$.

Fig. 135 – Simulated 2D RCS of arbitrary shaped ash particle ‘a’ in: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{vv}$, c) theta 0° $\sigma_{hh}$, and d) theta 0° $\sigma_{vv}$.

Fig. 136 – Simulated 2D RCS of arbitrary shaped ash particle ‘b’ in: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{vv}$, c) theta 0° $\sigma_{hh}$, and d) theta 0° $\sigma_{vv}$.

Fig. 137 – Location and equivalent colour of the each ash region. The approximated relative complex permittivity using $\text{dE}^{00}$ colour matching is illustrated in Table 21.

Fig. 138 – Simulated 2D RCS of arbitrary shaped ash particle ‘a’ with multi-dielectric regions: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{vv}$, c) theta 0° $\sigma_{hh}$, and d) theta 0° $\sigma_{vv}$.

Fig. 139 – Difference between solid and multi-dielectric simulated 2D RCS of arbitrary shaped ash particle ‘a’: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{vv}$, c) theta 0° $\sigma_{hh}$, and d) theta 0° $\sigma_{vv}$.

Fig. 140 – Simulated 2D RCS of arbitrary shaped ash particle ‘b’ with multi-dielectric regions: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{vv}$, c) theta 0° $\sigma_{hh}$, and d) theta 0° $\sigma_{vv}$.

Fig. 141 – Difference between solid and multi-dielectric simulated 2D RCS of arbitrary shaped ash particle ‘b’: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{vv}$, c) theta 0° $\sigma_{hh}$, and d) theta 0° $\sigma_{vv}$.

Fig. 142 – Example of ash created from biomass exposed to temperatures above the ember point of the messmate eucalypt biomass >450 °C.

Fig. 143 – Effective exposed temperature probability distribution for the given $\Delta I_{rgb}$ matching method with respect to the normalized RGB colour model of the messmate eucalyptus tree.

Fig. 144 – Effective exposed temperature probability distribution for the given $\Delta E^{*00}$ matching method with respect to the normalized LAB colour model of the messmate eucalyptus tree.

Fig. 145 – Box-plot of the error distribution for the two best colour matching methods used to approximate the exposed temperature PDF’s.

Fig. 146 – Examples of the formation of ash from eucalypt leaf structures in a) poor combustion conditions, b) good combustion conditions. Red circles represent the formation of small carbonaceous regions contributing to the lower exposed temperature distributions.

Fig. 147 – A 3D representation of the temperature profile for the particle populations with respect to their projected surface area. Colour bar represents frequency of particles.
Fig. 148 – A 3D representation of the temperature profile for the particle populations with respect to their aspect ratio. Colour bar represents frequency of particles.

Fig. 149 – 3D illustration of the dynamic RCS measurements system housed inside RMIT’s millimetre wave anechoic chamber. Biomass samples are heaped onto a paper conveyer belt which is driven by a high precision Arcus Technologies NEMA 17 PC programmable stepper motor. The stepper is shielded using absorber foam.

Fig. 150 – Illustration of sample preparations and image of falling particles used in the dynamic RCS measurement system. Samples stamped from Eucalypt biomass then dried. Samples then placed on paper conveyer where a stepper motor drives them over edge.

Fig. 151 – Filtered reflectivity ($\eta$) for dried messmate eucalypt disks. Red arrows provided on sampling range to indicate location of biomass measurements (i.e. 6, 12, 18 and 24). All other samples are background noise with the inclusion of the stepper motor and paper conveyer movements. Atm. Temp. 23 °C, RH 36%.

Fig. 152 – Box-plot of measured vs. simulated reflectivity for controlled eucalypt leaf particles based on measured relative complex permittivity and known geometry at 37.4 GHz. Measured data used to confirm the expected simulation scattering responses above the measurement noise floor (NF). Atm. Temp. 23 °C, RH 36%.

Fig. 153 – Simulation framework showing the major components of the CST MWS/MATLAB co-simulations scheme for analysing the reflectivity of ash particles.

Fig. 154 – Illustration of the simulation planes (top left to right 90° to 0° elevation angles) and geometric modelled ash particles (bottom) used within the CST MWS simulations. A total of 30 ash particle present within this illustrated model, representing a maximum concentration of 26.59 g/m³.

Fig. 155 – Horizontal reflectivity of messmate eucalypt ash over a wide range of frequencies where a) fluttering mode with beam elevation angle at 90°, b) fluttering mode with beam elevation angle at 45°, c) fluttering mode with beam elevation angle at 0° and d) random chaotic mode. Concentration (g/m³) of the ash particles is represented by the colour of each point.

Fig. 156 – Differential reflectivity ($\eta_{hh}/\eta_{lv}$) of messmate eucalypt ash over a wide range of frequencies where a) fluttering mode with beam elevation angle at 90°, b) fluttering mode with beam elevation angle at 45°, c) fluttering mode with beam elevation angle at 90° and d) random chaotic mode. Concentration (g/m³) of the ash particles is represented by the colour of each point.

Fig. 157 – Cross-polarization reflectivity of messmate eucalypt ash over a wide range of frequencies where a) fluttering mode with beam elevation angle at 90°, b) fluttering mode with beam elevation angle at 45°, c) fluttering mode with beam elevation angle at 0° and d) random chaotic mode. Concentration (g/m³) of the ash particles is represented by the colour of each point.

Fig. 158 – Illustration of the resolute volume for a scattering volume.

Fig. 159 – Example of an antennas farfield radiation pattern with colour map of realized gain.

Fig. 160 – Theoretical horizontally polarised 2D mono-static RCS ($\sigma_{hh}$) of the L-Disks of messmate eucalypt ash with the geometric and RF properties outlined in Table 17 with respect to frequency. a) 200°C, b) 300°C, c) 400°C, and d) 500°C.
Fig. 161 – Theoretical 2D vertically polarised mono-static RCS ($\sigma_{vv}$) of the L-Disks of messmate eucalypt ash with the geometric and RF properties outlined in Table 17 with respect to frequency. a) 200°C, b) 300°C, c) 400°C, and d) 500°C .......................................................... 256

Fig. 162 – Messmate Eucalypt (Eucalyptus obliqua), a) large red Messmate eucalypt tree, b) example of foliage, c) example of the texture and colour of the bark, c) seed pods, d) top side of leaves, and e) under-side of leaves. ............................................................................................................. 259

Fig. 163 - Red Ironbark (Eucalyptus tricarpa), a) large red Ironbark tree, b) example of the texture and colour of the bark, c) texture and colour of branches and seed pods, d) top side of leaves, and e) under-side of leaves. ................................................................... 260

Fig. 164 - Spotted Gum (Eucalyptus maculata), a) large spotted gum tree, b) example of the texture and colour of the main trunk, c) texture and colour of branches, d) top side of leaf, and e) under-side of leaves. ................. 261

Fig. 165 – Blackwood Wattle (Acacia melanoxylon), a) example of a juvenile tree, b) example of a juvenile seedling, c) colour and texture of the bark, d) example of the foliage, e) length of a single needle.............. 262

Fig. 166 – Austral Bracken Fern (Pteridium esculentum), a) single fern in its natural ecosystem, b) example of a highly populated Bracken Fern population, c) texture and colour of the stem, d) top side of leaf, and e) under-side of leaves. ............................................................................................. 263

Fig. 167 - Sheoak (Casuarina glauca), a) example of a mature sheoak tree, b) example of a juvenile sheoak tree, c) colour and texture of the bark, d) example of the foliage, e) length of a single needle, e) example of the seed pods. ........................................................................................................... 264

Fig. 168 - Radiata Pine (Pinus Radiata), a) example of the radiate pine bark, b) foliage of the pine, c) pine cone, d) example of the pine needles, e) examples of a radiate pine plantation in the Otway’s Victoria ......... 265

Fig. 169 - Cypress (Cupressus Leylandii), a) example of a Leyland Cypress tree, b) example of seed pod, c) colour and texture of the bark, d) example of the foliage, e) length of a single needle ........................................... 266

Fig. 170 - Outline of image correlation/matching process used to determine the PDF and error model of fire generated particles. .................................................................................................................... 268

Fig. 171 – Definition of the projected area, aspect ratio thickness for planar type ash particles ..................... 269

Fig. 172 – Definition of the projected area, aspect ratio thickness for needle type ash particles ..................... 269

Fig. 173 - Example of an a) high resolution scan of a dried eucalypt leaf showing small variation in illumination created during the scanning process (image is an enlargements of a 3.4mm x 3.4mm patch), b) same image with implementation of the pixel normalization process................................................................. 271

Fig. 174 – Flow chart showing the relative steps required to ascertain a distribution for the complex permittivity of an individual ash particle based on its exposed temperature......................................................... 272

Fig. 175 - Cubic extrapolation of mean normalized RGB values of messmate eucalypt leaves at various temperatures. Also included is a colour bar showing the normalized RGB model ......................................................... 273

Fig. 176 – Equivalent average CIELAB values of the messmate eucalypt leaves at various temperatures. ..... 274
Fig. 177 – Cubic extrapolation of mean normalized RGB values of messmate eucalypt leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures. ................................................................. 277

Fig. 178 – Equivalent average CIELAB values of the messmate eucalypt leaves at various temperatures. .... 278

Fig. 179 – Cubic extrapolation of mean normalized RGB values of red ironbark eucalypt leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures. ................................................................................................................................. 279

Fig. 180 – Equivalent average CIELAB values of the red ironbark eucalypt leaves at various temperatures. 279

Fig. 181 – Cubic extrapolation of mean normalized RGB values of spotted gum eucalypt leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures. ................................................................................................................................. 280

Fig. 182 – Equivalent average CIELAB values of the spotted gum eucalypt leaves at various temperatures. 281

Fig. 183 – Cubic extrapolation of mean normalized RGB values of blackwood wattle leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures. ................................................................................................................................. 282

Fig. 184 – Equivalent average CIELAB values of the blackwood wattle leaves at various temperatures. .... 282

Fig. 185 – Cubic extrapolation of mean normalized RGB values of Austral Bracken Fern leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures. ................................................................................................................................. 283

Fig. 186 – Equivalent average CIELAB values of the Austral Bracken Fern leaves at various temperatures. 284

Fig. 187 – Cubic extrapolation of mean normalized RGB values of radiata pine needles at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures. ................................................................................................................................. 285

Fig. 188 – Equivalent average CIELAB values of radiata pine needles at various temperatures. .............. 285
List of Tables

Table 1: Australian Bureau of Meteorology © radar site and time to detection of the Kilmore East Fire ..........20

Table 2: Open fire test parameters ..................................................................................................................42

Table 3: Summary of the PDF distributions of ash particles created from various plant and tree species ....83

Table 4: Base Elemental properties of Messmate Eucalypt Ash ..................................................................90

Table 5: Base Elemental properties of Blackwood Wattle Ash ..................................................................91

Table 6: Base Elemental properties of high temperature ash .....................................................................91

Table 7: Solid Density of Ash ..........................................................................................................................98

Table 8: Summary of Physical properties on Messmate Eucalypt .................................................................102

Table 9: Fluidic properties of Eucalypt Ash particles ....................................................................................109

Table 10: Fluidic properties of Radiata Pine Ash particles .............................................................................111

Table 11: Volume Fraction Values for Ash Samples .....................................................................................124

Table 12: Summary of results at mid-band frequency (10 GHz) ................................................................131

Table 13: Summary of mixing law results at mid-band frequency (10 GHz) ..................................................136

Table 14: Summary of fitting errors for measurements and mixing model ...................................................136

Table 15: Summary of mixing law results at mid-band frequency (10 GHz) ..................................................159

Table 16: Summary of fitting errors for measurements and mixing model ...................................................159

Table 17: RMS Error between measured and unified mixing law to 400°C at 10GHz .................................169

Table 18: RMS Error between measured and unified mixing law with moisture ............................................175

Table 19: Measurement and Simulation parameters .......................................................................................189

Table 20 – 90° Null Locations with Respect to d/λ and C/λ ratio ................................................................197

Table 21: Summary of Approximated Relative complex permittivity Within each Particle Region at 10 GHz 201

Table 22: Measured Normalized mean RGB and LAB values for Eucalyptus obliqua ...............................277

Table 23: Measured Normalized mean RGB and LAB values for Eucalyptus tricarpa .................................278

Table 24: Measured Normalized mean RGB and LAB values for Eucalyptus tricarpa .................................280
Table 25: Measured Normalized mean RGB and LAB values for Acacia melanoxylon

Table 26: Measured Normalized mean RGB and LAB values for Pteridium esculentum

Table 27: Measured Normalized mean RGB and LAB values for Pinus Radiata
## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>Permeability</td>
</tr>
<tr>
<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer</td>
</tr>
<tr>
<td>BIRD</td>
<td>Bi-Spectral Infrared Detection</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of Light (~$3 \times 10^8$)</td>
</tr>
<tr>
<td>FLIR</td>
<td>Forward Looking Infrared</td>
</tr>
<tr>
<td>GEO</td>
<td>Geo-Stationary Orbit</td>
</tr>
<tr>
<td>GHz</td>
<td>Giga-Hertz ($1 \times 10^9$ Hz)</td>
</tr>
<tr>
<td>GOES</td>
<td>Geostationary Operational Environmental Satellite</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz (cycles per second)</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ISM</td>
<td>Inverse Scattering Model</td>
</tr>
<tr>
<td>Ka-Band</td>
<td>Frequency Band 26.5-40 GHz</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light Detection and Ranging</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-Electro-Mechanical Systems</td>
</tr>
<tr>
<td>MHz</td>
<td>Mega-Hertz ($1 \times 10^6$ Hz)</td>
</tr>
</tbody>
</table>
MODIS Moderate-resolution Imaging Spectro-radiometer
NIH National Institute of Health
NOAA National Oceanic and Atmospheric Administration
NSW New South Wales
Radar Radio Detection and Ranging
RGB Red-Green-Blue
SAR Synthetic Aperture Radar
SODAR Sonic Detection and Ranging
UHF Ultra-High Frequency
VHF Very-High Frequency
VIC Victoria
X-Band Frequency Band 8.4-12.5 GHz
ε Permittivity
λ Wavelength
μm Micro-meters, microns
GEV Generalized Extreme Value
PDF Probability Distribution Function
dpi Dots per inch
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSLR</td>
<td>Digital Single-Lens Reflex (Camera)</td>
</tr>
<tr>
<td>MDS</td>
<td>Minimum Detectable Signal (Watts)</td>
</tr>
<tr>
<td>PPI</td>
<td>Plan-Position Indicator</td>
</tr>
<tr>
<td>RHI</td>
<td>Range-Height Indicator</td>
</tr>
<tr>
<td>PEC</td>
<td>Perfect Electric Conductor</td>
</tr>
<tr>
<td>WPL</td>
<td>Wave Propagation Laboratory</td>
</tr>
<tr>
<td>LDR</td>
<td>Linear Depolarisation Ratio</td>
</tr>
<tr>
<td>MUT</td>
<td>Material Under Test</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyser</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequencies</td>
</tr>
<tr>
<td>$F_I$</td>
<td>Fuel Loading Factor</td>
</tr>
<tr>
<td>$m_w$</td>
<td>Wet Mass (kg)</td>
</tr>
<tr>
<td>$A$</td>
<td>Area ($m^2$)</td>
</tr>
<tr>
<td>$m_d$</td>
<td>Dry Mass (kg)</td>
</tr>
<tr>
<td>DoC</td>
<td>Degree of Curing (%)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Emissivity</td>
</tr>
<tr>
<td>MoM</td>
<td>Method of Moments</td>
</tr>
<tr>
<td>RCS</td>
<td>Radar Cross-Section</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Radar Cross-Section</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
</tbody>
</table>
Chapter 1 – Introduction

1.1 Introduction

Remote sensing technologies are fast becoming the most attractive option for monitoring natural phenomena in today’s modern society [1, 2]. Moreover, there is a growing expectation that countries will invest in technologies which protect, assess, alert and inform the wider community of pending danger. The rapid expansion in advance sensing technologies is primarily driven by the need to better understand natural phenomena, with the primary objectives of protecting life and minimising risk. In many cases, a country’s geographical location will dictate the types of natural phenomena that may occur. Countries such as Japan, which lie on the pacific ring of fire are more prone to earthquakes, volcanic eruptions, landslides and tsunamis, while low lying tropical areas may be more prone to flooding. Australia, being one of the driest continents in the world, coupled with its highly flammable vegetation, has a significantly high fire risk [3-6]. The need for viable remote sensing technologies to track forest fires has never been greater [1]. On the 7th of February 2009, Australia suffered one of its largest, most destructive bushfires in the nation’s history. The systems in place were not able to track the fire progression with high enough feudality [1], thus proving that they are inadequate in overcoming large scale fire emergencies.

Over the last few decades, great progress has been made into understanding the behaviour of bushfires. The advances in predictive models have moved leaps and bounds due to the implementation of remote sensing data [7, 8]. Even so, further research must be undertaken to provide a more robust analysis of how fires dynamically interact with vegetation and the atmosphere.

Radar (Radio Detection and Ranging), is a device which transmits an electromagnetic signal, senses received echoes and then analyses these echoes from a reflecting target [9]. It has unique system characteristics favourable for tracking fires, namely its active sensing capability which is not currently available with passive optical systems. Radar gathers
information about a target of interest, such as its range, bearing, velocity, size and basic identification. This data can be greater than 4-dimensional (4D) in size, providing valuable information not only on where fire activity is present, but on how a fire is behaving. The implementation of radar when coupled with other active sensing technologies can provide a vital sensing capability not currently available to emergency services.

1.2 Radar, Radar Cross-Section, Frequencies and Ash

Since the inception of radar in the 1940’s, the development of systems for remote sensing applications is becoming more prevalent. Examples of such systems include collision avoidance, Doppler weather (ground and aircraft), ground penetrating, marine, snow avalanche, and volcanic eruption detection radars, to name a few. In low to medium range applications (≤100 km), the cost of these systems has also substantially decreased due to the availability of solid state technologies such as monolithic microwave integrated circuits (MMIC’s). These miniature RF circuits are complemented by the advancements in computing power and digital signal processing (DSP) platforms such as dedicated DSP processors and field-programmable gate arrays (FPGA). Development in MMIC’s has not only led to better system performance but has also opened avenues for utilising higher frequency bands, thus offering new avenues for research and development in a variety of remote sensing applications.

The building blocks required for designing a radar system begin with an in-depth knowledge of its intended purpose and target classification requirements, including assessing the target’s radar cross-section (RCS). The standard definition of the RCS is “4π times the ratio of the power per unit solid angle scattered in a specified direction, to the power per unit area of an incident plane wave scattered from a specified direction” [9]. This forms the basis for the three radar configurations and scattering cases which include:-

- **Monostatic or backscatter RCS is when the incident and reflected scattering directions are coincident but opposite [9].**

- **Forward-scatter RCS is where the energy reflected or scattered is in the same direction as the propagation path of the incident wave [9].**
• *Bi-static RCS is when the energy reflected or scattered is in any direction other than the incident direction or that which is opposite of the incident direction* [9].

The RCS of a target is dependent on many physical and electromagnetic properties. These include: geometric properties, dynamic properties, electromagnetic or RF material properties, transmit frequency, transmit polarisation, receive polarisation and incident angle.

The geometric properties define the volumetric shape of a scattering target while the dynamic properties, (in the case of natural targets), define its orientation relative to a propagating field. Finally, a target’s electromagnetic material properties are defined by the complex permittivity and permeability of its base material. The complex permittivity is defined as a macroscopic material property which relates the electric flux density $D$ to the electric field $E$ of a propagating electromagnetic wave through a medium [10]. Moreover, the complex permeability relates the magnetic flux density $B$ to the magnetic field $H$ [10]. These material properties define the maximum possible scatter that a target of the same geometric shape can achieve.

For dispersed mediums such as those represented by particulates suspended within a volume, the RCS becomes representative of the total possible scatter by all bound targets. This is often referred to as volume scatter or reflectivity. Here, scatter is caused by inhomogeneities within a scattering volume. The inhomogeneities can be described as being discrete particles, discrete structures or continuous spatial variations of refractive index within free-space [10]. By changing the refractive index of free-space and hence its wave impedance, the energy of an incident electromagnetic wave is scattered in all directions.

The volume of scattering is known as the volumetric resolution cell which defines the minimum volume and therefore the minimum spatial resolution for which radar can distinguish differences between multiple targets in three-dimensional (3D) space. Dispersed mediums are generally associated with meteorological remote sensing. Common dispersed mediums include rain precipitation, snow, volcanic ash, dust, insects and finally, fire smoke plumes.

When describing dispersed mediums, it is common practice in most cases to define the scattering by a Rayleigh scatter distribution. Depending on the ratio between wavelength and particle size, this may also be described as a Mie scatter distribution or a combination of the two. For non-uniformly shaped particles, the scattering becomes more random and extremely complex to analyse. Here, these types of scattering mediums do not always comply with a Rayleigh or Mie distribution. The particulates found in forest fire smoke plumes are
inherently non-uniform in shape and inhomogeneous in structure [11]. Biomass cellular structures form the framework for these complexities which require further investigation from the existing body of knowledge. Due to the structure of ash, the resultant scattering may not fully comply with a Rayleigh or Mie distribution and so the fundamental interactions between electromagnetic waves and the particulates requires further examination.

Considering the wide variety of tree and plant species found throughout the world’s forests, different types of biomass and their scattering characteristics must be known in order to build a fundamental understanding of their scattering properties. Once the scattering mechanisms behind dispersed mediums such as ash particulates are firmly understood, an inverse scattering model can be implemented. With the capability to correlate measured scattering fields to the physical properties of a target, the inverse scattering model is of great importance. In the case of naturally occurring phenomena, this capability relies heavily on statistical methods. For ash particulates suspended within smoke plumes, the correlated scatter may be used to represent properties of fires such as intensity, size, water content, mass of consumed biomass and vegetation types.

1.3 Motivation

When examining the extent of fire detection technologies available within Australia, the abundance of real-time systems is restricted to those operating in the optical and infrared (IR) regions of the electromagnetic spectrum (EM). High capacity computing, coupled with the increase in cheap microwave components, has now opened the door for active sensors to be implemented to complement existing optical systems. Furthermore, there is the capability to analyse real-time fire weather, plume size and direction.

Fundamentally, the implementation of radar for fire detection has been limited by physical technological boundaries, cost and understanding of the principle scattering mechanisms. Although technological advances in RF system design, recent cost reductions and better signal processing have solved many of these limitations, fundamental scattering mechanisms are still poorly understood. The motivation of this dissertation is to provide a better understanding of these fundamental scattering sources from fires. Ultimately, this research hopes to further diversify and improve current fire sensing technologies in an effort to better analyse and manage large fire threats. It is believed that active-based sensors can play a vital role in fulfilling this aim.
1.3.1 Thesis Overview

This dissertation aims to investigate the primary scattering characteristics of forest fire ash through the study of their geometric properties, dynamic behaviour, relative complex permittivity and complex permeability, volumetric radar cross-section and extinction cross-section. The scattering characteristics at two spectral bands, being X-Band (8GHz – 12GHz) and Ka-Band (26.5GHz – 40GHz), have been analysed in detail. These two bands represent a comparison in the scattering characteristics between popular X-Band radar systems and emerging systems in the low millimetre-wave bands.

Chapter 2 presents a detailed literature review. The review looks explicitly at the use of radar in applications of fire observation. This chapter also reviews the current literature on observations of fire smoke plumes using UHF, L, C, S, X and W-band Doppler and non-Doppler weather radar systems. A case study of weather radar observations of forest fires is presented for three fires, including the major Australian Black Saturday fires which occurred on the 7th of February 2009.

Chapter 3 presents a detailed investigation into the geometric and physical material properties of leaves. The geometric properties are reviewed to gain insight into the expected baseline shapes of ash particles. Material properties such as elemental composition, moisture absorption rates, porosity, mass variations and colour changes with temperature are examined to understand the behaviour of the organic cell structures. Finally, the dynamic behaviour of ash particles dispersed within a volume of space is explored. These physical properties are all determined experimentally and are based on a variety of common Australian flora. However, samples have also been explored for non-native species.

Chapter 4 reviews the electromagnetic material properties of ash particles. This chapter is dedicated to examining both the relative complex permittivity and permeability of ash samples from particles prepared in two temperature regions. The first region represents that which is found between the unburnt state (22 °C) to 600 °C. Here, controlled samples have been prepared at specific temperature levels and their relative complex permittivity and permeability values measured. The second regions is that representing high temperatures. Within this region samples were created in fires with flame temperatures from 800 °C – 1200 °C.
Chapter 5 explicitly observes the effects of RCS, attenuation and validation of a co-simulation scheme developed to simulate scattering from ash particles. The co-simulation scheme utilises the statistical models developed in Chapter 2. Validation is carried out through dynamic measurements using a purposely built measurement system, housed inside an anechoic chamber. There is also a short study on the transmission properties of small fires and their effects on both the magnitude and phase of a propagating signal.

Chapter 6 presents a summary and discussion about this dissertation. It will provide avenues for further investigation and suggest future work.
1.4 List of Publications

Below is a listing of all peer reviewed publications related to the research carried out in this dissertation. The first listing details all the peer review journals and letters published in relation to the research area. The second listing details all the peer reviewed conference papers.

1.4.1 Peer-Reviewed Journal Articles


1.4.2 Peer-Reviewed Conference Proceedings


K. Ghorbani, **T. Baum** and L. Thompson (2012). Properties and Radar Cross-Section of Forest Fire Ash Particles at Millimeter Wave, European Radar Conference (EuRAD). Amsterdam, the Netherlands


1.5 Original Contributions

This dissertation investigates the primary scattering characteristics of forest fire ash. A summary of the novel and scientific contributions to the existing body of research is listed below.

- Statistical distributions of the geometric properties of ash particles have been evaluated in detail. This also includes a detailed analysis on the physical changes of eucalypt leaf cell structures when exposed to various temperatures.

- An image processing method has been developed and implemented to further analyse the exposed temperature distribution of individual fire-generated ash particles.

- The relative complex permittivity and permeability of ash particles at various temperatures and over two frequency bands have been investigated and analysed.

- An empirical mixing law model to describe the effects of the relative complex permittivity of ash particles with changes in material porosity has been developed.

- A study of the baseline relative complex permittivity and permeability of the underlying organic material which constitutes leaf structures has been conducted.

- A novel automated measurement system to analyse the dynamic radar cross-section and attenuation of ash particles at Ka-Band has been developed.
Chapter 2 - Literature Review

2.1 Introduction

This chapter examines the scope of literature that details the interactions between radar signals and smoke plumes. It will review the extent of existing fire detection technologies and proposed sensing devices. It will also review the fundamental principles of electromagnetic scattering and their implication in understanding how radar works. Finally, various methods for studying the RF material properties of media within smoke plumes will be demonstrated.

2.2 Forest Fire Remote Sensing

Currently, all existing remote sensing technologies for early stage fire detection focus on systems which fall under the heading of passive technologies. These technologies look for specific signatures of fires, resulting from the release of smoke into the atmosphere and/or heat signatures from burning biomass. Like all observational systems, they rely on these signatures to be available within the ‘line-of-sight’ before a fire assessment can be confirmed. These implemented technologies are generally found on ground platforms and incorporate passive sensors such as optical systems operating in high dynamic range grey scale and/or colour, infrared (IR) [12-17] and at the other side of the scale, small wireless sensor networks using optical, IR, thermal and/or smoke detection sensors [18-22]. In development are passive microwave detection technologies which use thermal noise detection [23-25]. Also falling under this heading are the geo-spatial platforms which have been extensively used to assess fire damage and hot-spot detection.

The most utilised sensors for fire detection, monitoring and fire weather include the NOAA Advanced Very High Resolution Radiometer (AVHRR) [26-28], Geostationary
Chapter 2 - Literature Review

Operational Environmental Satellite (GOES) and Moderate-resolution Imaging Spectroradiometer (MODIS) [29]. Recent advances in IR processing algorithms have also seen more focus placed on IR sensors such as the German aerospace’s (DLR) Bi-Spectral Infrared Detection (BIRD) and the recently launched TET-1 satellite [30-32]. These satellites are experimental test platforms for developing advanced digital signal processing algorithms. In most cases, the geo-spatial systems currently available do not possess the capability for real-time continuous surveillance. Those that do are generally within geostationary orbit and have poor spatial resolution. High resolution, low-earth orbiting satellites which can observe the southern hemisphere in near real-time are still in development and are decades away from becoming a reality.

Moving towards active sensing technologies, a number of benefits not currently available with traditional fire detection technologies can be obtained. The most important of which is the ability to volumetrically analyse fires. Whether this is achieved using ground, aerial or space platforms with sensors utilising different spectral bands is still widely open for discussion [33]. Active technologies which have been suggested for fire detection including; Light Detection and Ranging (LIDAR) [34-39], Sonic Detection and Ranging (SONDAR) [40] and Radio detection and ranging (Radar) [41]. A hybrid sensing technology between active and passive sensing is Synthetic Aperture Radar (SAR). This technology uses active microwave electromagnetic radiation to image structures. SAR has been implemented for post fire monitoring in satellites such as European Remote-Sensing satellite (ERS), TerraSAR-X and EnviSAT. Synthetic Aperture Radar systems can also be implemented in Arial platforms.
Chapter 2 - Literature Review

2.3 Radars Observing Fire

Radar’s ability to observe scattering from smoke plumes has been well established since the birth of radar itself. The first reported observation of scatters originating directly from a known smoke plume dates back to Jones in 1949 [42]. Since this time, there has been a multitude of publications focussing on the use of radar for observing and understanding fires. This breadth of literature can be divided into three categories which explore the use of radar for the remote sensing of fires, understanding scattering mechanisms and using radar for fire detection.

Remote sensing of fire using radar has primarily focused on aiding research into fire behaviour and the interactions between fire and the atmosphere [34, 38, 43-46]. Traditionally, existing weather radar systems have been the primary radar based tool for observations of fires, however; other active sensing systems such as lidar and sondar have also been investigated [34-36, 38-40, 47]. Due to the active sensing component of radar, it is able to provide invaluable data on how the convection column develops over time. This allows for observations of smoke columns upwards of 1.8 km in altitude and distances upwards of 100 km from the radar’s position [34, 38, 39, 41-46, 48-50]. Here, the maximum altitude is limited by the injection height of the plume and not the performance of the radar. Coupled with this is the ability to measure Doppler shifts, providing localised wind speeds and information about the development of large rotation vortices such as horizontal roll vortices (HRV) and transverse roll vortices (TRV) [51-53]. Recently, radar has also been investigated as a tool for monitoring air quality surrounding large fires [44]. The introduction of polarimetric weather radars has also illustrated clear and distinct differences between smoke plumes and clouds [34, 38, 41, 45, 46, 54, 55]. These differences are now being investigated as a possible means for using existing weather radar systems to sense the presence of fire activity [41, 44, 46, 55].

The application of radar for remote sensing of fires is underutilised when compared to traditional optical and infrared sensors [38, 44]. Possible disadvantages of using radar for fire sensing applications centre on its spatial resolution and limited availability [34, 38, 44-46, 50]. Ideally positioned to limit the influences of ground clutter, weather radar has difficulties in sensing scattering at low grazing angles. Depending on the topology of the terrain within the maximum detectable range, these systems are limited to sensing large fires typically ranging upwards of tens to possibly hundreds of acres in size [34, 43, 46]. The use of low
power, low cost, modulated wide-band radars may provide an alternative system design to improving the spatial resolution. These types of radar are now preferred for remote sensing applications over pulsed radar, due to the availability and economical costs of high power, high performance Gallium Arsenide (GaAs) and Gallium Nitride (GaN) MMIC’s [56-62].

Understanding scattering mechanisms is an important step in connecting radar reflectivity to the dynamics of a medium. This is commonly known as the inverse scattering problem and forms the basis for many remote sensing applications. The implementation of the inverse scattering problem for radar has many real-world applications and has already been applied to weather radar. Extensive research has been carried out to characterise the reflectivity of weather events [63]. Today we rely on weather radar data for prediction and characterisation of the types of liquid/solid mediums to precipitate from clouds such as rain, hail, snow and drizzle [63]. This also includes a quantitative analysis of the amount of liquid/solid mediums present within clouds.

The fundamental scattering characteristics of forest fire smoke plumes are still widely debated, namely surrounding the actual sources of the scatter present within the plume. Radar reflectivity from fire plumes has been associated with ash particle scatter [34, 38, 44, 45, 48, 54, 55, 64-67], condensed water nuclei on smoke particles [38, 68, 69], precipitation [70], clear-air/Bragg scatter [38, 44, 45, 54, 55, 64-66, 71] and weakly ionised alkali salts [72-74]. As little is still known about scattering sources originating within plumes, this list may only be a simplified representation of what is an extremely complex natural phenomenon. The use of co and cross-polarisation measurements of plumes (also known as polarimetric measurements) has identified larger ash particles as one of the main candidates for the scattering [34, 38, 43, 54, 55, 64, 66]. However, measurements taken from fires using a number of different frequency bands have indicated interactions between clear-air/Bragg scatter, incoherent particle scatter and coherent particle scatter [64, 66]. The cohesion between these studies has also limited the ability to correlate data on these different scattering sources. This has been limited by the small number of published studies investigating the fundamental scattering sources. Furthermore, little is known about the relative complex permittivity and permeability of larger ash particles [34, 38, 43, 54, 55, 64, 67]. Typically, the relative complex permittivity of volcanic ash has been assumed to be a good comparison. However, this assumption is purely based upon the availability of measured data used to understand the refractive index of volcanic ash plumes. Changes in the relative complex permittivity of fire ash due to variations in their exposed temperature are currently unidentified.
Research into the geometric properties of large forest fire ash particles is also poorly documented. Of those studies, half have examined ash particles taken from man-made fuel sources such as apartment fires, industrial fires, rubbish dumps or wood storage fires [42, 45, 48, 64-66]. For those particles derived from organic biomass within natural forest fires, little is known about the shape of these larger particles with respect to their radar cross-sections or how their physical structures vary between different plant and tree species. Also, the concentration of these particles must be known to determine the scattering perceived by volumetric radar measurements [34, 43, 67, 75, 76].

Measurements taken from polarimetric radar have indicated needle-like structures based on the depolarisation ratio between orthogonally polarised waves [34, 38, 44, 45, 54, 55, 64-66]. However, it is not known if these measurements are an indication of particle geometry or a consequence of the particles’ dynamic behaviour inside a plume [43, 77]. There has also been some indication of coherent particle scatter [64-66]. This arises from a half-wave resonance between neighbouring particles, resulting in constructive interference. This illustrates that the particles’ dynamic behaviour may be playing an important role in producing detectable scatter. Early reports of radar observing fires found contrary views to what role particles play in the scattering mechanism. It was shown by Reid and Vines that particle scatter cannot exist due to the lack of concentration of larger particles within a plume [43]. However, the exact concentration of larger particles was not known at that time [43].

It has also been shown that ash can act as a collecting point for condensing water vapour arising from the large amounts of moisture present within biomass [68, 69, 76, 78]. What effects this has on the relative complex permittivity of the particles is yet unknown, which presents as an obstacle when considering the uptake rate of moisture within larger ash particles. This uptake of moisture may also vary based on a particle’s altitude, temperature, pressure and relative humidity of the surrounding atmosphere [68, 69, 78].

At higher altitudes the large amount of moisture held within the biomass can also form pyro-cumulonimbus clouds [50, 79]. These clouds can create rain precipitation due to the condensing water vapour held within them. This condensed water can then fall back towards the ground as rain precipitation or remain in the upper atmosphere and cause scattering towards electromagnetic waves. Pyro-cumulonimbus clouds may also be sources of lightning, hail and extreme winds [50, 79].

High wind speeds introduce another reflective phenomenon known as clear air/Bragg scattering. This type of scatter may be present within smoke plumes due to the large changes in the atmospheric refractive index caused by driving thermal dynamic forces created by fires.
The effects may be more prevalent on the perimeter of a plume where wind shear can occur due to Kelvin–Helmholtz instability. This instability is created due to the two fluid mediums possessing varying density and velocity. Clear air scatter has been well established for use in studying turbulent phenomena (such as those presented within fire plumes) within the atmosphere [80-82].

Finally, scattering arising from the plasma phase surrounding the flaming region of fires may also be present [73, 74, 83]. This plasma state is a result of the low energy required to ionize alkali salts present within biomass [84-92]. These mainly include magnesium, potassium and sodium salts making upwards of 10% by weight in some species. This however, varies considerably for plant species. For eucalyptus plants, this figure is in the order of 1% for sodium and potassium [90]. The availability of free electrons within the weakly ionised plasma determines the plasma frequency, which in turn interacts with an electromagnetic wave. At low frequencies, the plasma phase reflects electromagnetic radiation. At higher frequencies this is reversed and an electromagnetic wave experiences a relative complex permittivity of less than unity with a high attenuation constant [74]. Free electron count has been measured upwards of $1.47 \times 10^{16}$ Ne/m$^3$ for eucalyptus biomass burn at approximately 800 K ($527 ^\circ C$) [93]. Attenuation due to the plasma phase at microwave frequencies was measured to be at 2-4 dB, however this varies with time [93].
2.4 Australian Examples of Radar Observation of Forest Fires

The Australian Bureau of Meteorology operates a number of weather radars around the country. Observations of fire plumes are readily found on their weather radar scans and examples of these will be presented within this dissertation. The Black Saturday fires occurred in the state of Victoria on the February 7, 2009 and were the most devastating in the nation’s recorded history [1, 94]. The fires were the outcome of a sustained period of drought within the country, where below average rainfall had been recorded for more than twelve years. This was compounded by negligible precipitation in the previous two months leading up to the catastrophe [1, 94]. Weather conditions were extreme, with the daily temperatures reaching upwards of 45 °C in some locations and wind gusts upwards of 33 m/s. The relative humidity at the time of ignition was at approximately 15%, dropping to 10% and staying there for approximately 6 hrs. All of these weather conditions came together to produce rapidly moving, large-scale fires with devastating outcomes. The drought conditions were also very similar to Victoria’s second-most devastating fires, namely the 1983 Ash Wednesday fires. Here, below average rainfall was seen for some 10 months prior to the fires, with temperatures upwards of 40 °C, high wind conditions and a relative humidity of approximately 15%.

The well-documented progression of the Black Saturday fires makes it an ideal case study for observing the performance of existing weather radars. On February 7, 2009, the Australian Bureau of Meteorology had a total of four weather radar stations in observable range and in operation around the ignition time of the two main fires at Kilmore East and Murrindindi [1]. Three of the four observing radars were operating within C-Band (6GHz), with the exception of the Melbourne Laverton radar station. The Melbourne radar station houses a state-of-the-art Selex-Gematronik M1500-S1 S-Band radar (2.7-2.9GHz) with Doppler wind capability. A set of radar time sequences taken from the Melbourne radar and published by the Bureau of Meteorology is illustrated in Fig. 1.

The equivalent time sequence for the Doppler wind measurements taken from the same radar station is illustrated in Fig. 2. Both time sequences show the clear development of a number of smoke columns over time. The plume column developing at the top of the radar scans is that of the Kilmore East fire, while the lower column is that most likely originating from the Bunyip fire. The extent of what is causing the scatter in both fires is unknown,
however; there were significant formations of pyro-cumulonimbus clouds above the main plume. These pyro-cumulonimbus clouds can be observed from images taken from NASA’s MODIS sensor on board their AQUA satellite (see Fig. 3). Excellent correlation is displayed between the satellite imagery and radar scans [44, 72]. The composite satellite image/radar scan presented in Fig. 3 further illustrates this correlation. This radar scan was taken using the Melbourne Airport radar, as the main radar station in Melbourne Laverton was offline during the time the AQUA satellite passed over. As shown, the Melbourne Airport radar has considerably good correlations in mapping the extent of the smoke columns from the Kilmore East, Murrindindi and Bunyip fires. The Churchill complex fire becomes just visible to the radar while the Dargo fire falls outside the detectable range.

With consideration to the scans taken from the main radar station at Melbourne Laverton, looking at those scans from the main radar station in Melbourne Laverton, (see Fig. 1), further data presented by Cruz et. al. illustrates a vertical cut through the plume showing significant scatter at lower altitudes [94]. This suggests that the scattering observed was not solely originating from the formation of pyro-cumulonimbus clouds, but also other mediums inside the plume. Examining the Doppler wind scans presented in Fig. 2 for the Kilmore East fire, there is little visible indication of fire activity during the first few hours after its ignition. The Doppler signature from the Bunyip fire is however more clearly defined. This is due to its radial position from the radar station, giving the downwind plume a large detectable velocity component.

Using the radar scans published from all four stations in operation on Black Saturday, a relationship between range, time to first reflection and the relative location of reflectivity from the ignition point of the Kilmore East fire was assessed. This data is presented in Table 1. The Melbourne Laverton station detected the plume some nineteen minutes after the first call to emergency services [1]. The Melbourne Airport radar was closer in distance to the Kilmore East fire, however; its resolution was not as clear as the M1500-S1 radar at Laverton. With the exception of the Melbourne Laverton station, all three remaining radars operating in C-Band detected reflectivity from the plume in consecutive order, based on their range. The extreme case illustrated by the Bairnsdale radar, detected the plume column more than three hours after the fires began.
Fig. 1 – Example of equivalent rainfall rate for the black Saturday fires 7th February 2009 as taken by a Selex-Gematronic M1500-S1, S-band Doppler weather radar - Australian Bureau of Meteorology ©
Fig. 2 – Example of wind speed rate for the black Saturday fires 7th February 2009 as taken by a Selex-Gematronik M1500-S1, S-band Doppler weather radar - Australian Bureau of Meteorology ©
Table 1: Australian Bureau of Meteorology © radar site and time to detection of the Kilmore East Fire

<table>
<thead>
<tr>
<th>Radar Site</th>
<th>ID</th>
<th>Freq. Band</th>
<th>Model</th>
<th>Distance (km)</th>
<th>TFDR* (AEDT)</th>
<th>TD** (mins)</th>
<th>Rel. Dist.+ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melbourne Laverton (VIC)</td>
<td>IDR02</td>
<td>S-Band</td>
<td>M1500-S1</td>
<td>~66</td>
<td>12:06pm</td>
<td>~19</td>
<td>~1.3</td>
</tr>
<tr>
<td>Melbourne Airport (VIC)</td>
<td>IDR51</td>
<td>C-Band</td>
<td>-</td>
<td>~44</td>
<td>12:40pm</td>
<td>~53</td>
<td>~3.5</td>
</tr>
<tr>
<td>Bairnsdale (VIC)</td>
<td>IDR68</td>
<td>C-Band</td>
<td>DWSR-2502</td>
<td>~235</td>
<td>3:00pm</td>
<td>~193</td>
<td>~14.5</td>
</tr>
<tr>
<td>Yarrawonga (VIC)</td>
<td>IDR49</td>
<td>C-Band</td>
<td>WSR-81C</td>
<td>~167</td>
<td>1:00pm</td>
<td>~73</td>
<td>~7.15</td>
</tr>
</tbody>
</table>

* TFDR - time of first detectable reflection from archived radar scan
** TD - time to detection after first report of fire activity of the Kilmore East fire at 11:47 am AEST [1]
+ Rel. Pos. - Relative distance of first reflection to ignition point
Fig. 3 – Composite image of the Black Saturday fires taken using 250m MODIS on NASA’s AQUA satellite and the equivalent Australian Bureau of Meteorology © Melbourne Airport radar scan at 4:50 UTC (3:50pm AEDT) on the 2-Feb-2009. Image courtesy of NASA[95] and Australian Bureau of Meteorology ©

To assess the consistency of weather radar when detecting fires, two alternative cases have been investigated: the Anglesea basin controlled burn, carried out between March 27-28, 2009, and the Lake Thomson & Hotham Heights fires which occurred on January 24, 2013. These cases were selected due to their distinctly different terrains within Victoria. Anglesea lies on the south west coast of Victoria and is a small town which has a large black coal reserve. Its terrain comprises of shallow hills and valleys ranging from sea level to
approximately 115 metres in altitude. The Melbourne radar has almost direct line of sight to the township, with slight inclination in the terrain towards the coast end. Hotham Heights and Lake Thomson are located within the Alpine regions of Victoria. Both their terrains are extremely complex, with mountain ranges upwards of 1800 m. Ground clutter in these regions is significantly high and thus detection of fire activity via existing weather radars is also more challenging.

Despite being a controlled burn, the Anglesea basin fire eventually broke containment lines near the Alcoa Power Station northwest of the township. An image from AQUA’s MODIS sensor captured on March 28th 2009 shows the clear progression of the main plume column in an easterly direction (see Fig. 4). A composite satellite image/radar scan for the same local time as the MODIS image is also illustrated in Fig. 4. As shown, the resultant reflection from the smoke column is distinctive of that originating from a plume. It is known from images taken by MODIS that no pyro-cumulonimbus cloud formations were present on this day. The same can be said for an image taken by the author at Urquhart’s Bluff, on the outskirts of Anglesea which was captured on the same day (illustrated in Fig. 5).

The equivalent reflectivity of the plume is similar to that produced from light to moderate rainfall, demonstrating that the medium making up smoke plumes are highly reflective. The fire was situated some seventy kilometres from the radar station in a valley ranging from twenty to ninety metres in altitude. Within the radar’s line of sight, the terrain is considerably flat, ranging from twenty to one hundred and fifteen metres in altitude. The vegetation within this region is low density, scrubby bushlands, with significant ground cover including austral bracken fern (*pteridium esculentum*) and prickly tea-tree (*leptospermum continentale*) [73]. The area is also home to a large population of various eucalypt species, thus substantially contributing to the ground litter consumed during the basin fire. As the reflectivity of the plume is highly concentrated at its source, it is plausible that the main source of scatter is that directly resulting from large ash particles.
Fig. 4 – Composite image of the Anglesea basin controlled burn taken using 250m MODIS on NASA’s AQUA satellite at 4:50 UTC (3:50pm AEDT) and the equivalent Australian Bureau of Meteorology © Melbourne Laverton Selex-Gematronik M1500-S1, S-band Doppler weather radar scan at 4:54 UTC (3:54pm AEDT) on the 28th March 2009. Image courtesy of NASA[96] and Australian Bureau of Meteorology ©

In contrast to the Anglesea basin fire, the Lake Thomson and Hotham Heights fires are located in the alpine regions of Victoria. Both fires were thought to have been started by a number of lightning strikes. These strikes ignited numerous spot fires that were of great concern due to Lake Thomson’s close proximity to the water catchment supplying Melbourne. The MODIS image showing the extent of both fires on January 24, 2013 is illustrated in Fig. 6.
Fig. 5 – (Top) Photo taken from Urquhart’s Bluff at 3:30pm AEST of the Anglesea basin fire on the 28-Mar-2009, the image showing the extent of the solid particulates ejected into the atmosphere by the thermodynamic cycle of the fires and the lack of pyro-cumulonimbus formations above the fire. (Middle) Typical Biomass consumed during the fire. (bottom) Aftermath of the Anglesea basin fire.
The formation of pyro-cumulonimbus clouds was seen only in the Hotham Heights fire as illustrated by the MODIS image. The extent of radar reflectivity from both fires is illustrated in Fig. 6. Again, the image represents a composite satellite image/radar scan, however; the reflectivity from the Hotham Heights fire is that originating from the Yarrawonga radar station, while the reflectivity from the Lake Thomson fire is that from the Melbourne Laverton radar station. This was because the Hotham Heights fire was not visible by the Melbourne Laverton radar and vice-versa. The Lake Thomson fire was situated some 150 km from the Laverton radar station at an altitude ranging from 550 m to 1050 m. Its reflectivity is that equivalent to very light rainfall.

The Hotham Heights fire burnt in terrain ranging from approximately 130 m to 1850 m in altitude. Again, the reflectivity of the Hotham Heights fire was equivalent to that of very light rainfall. Due to the significantly complex terrain, it is likely that the Yarrawonga radar was detecting the formation of the pyro-cumulonimbus cloud above the mountain range. The location of the scatter from the radar scan and the formation of the pyro-cumulonimbus cloud support this notion. In the case of Lake Thomson, particle scatter may be the primary cause of the reflectivity detected by the radar. This is illustrated by the dark coloured region of the plume as shown by the arrow within the AQUA image of Fig. 6. This darker region may also be the result of different types of vegetation or possibly water content inside the biomass. Regardless of the scattering sources, it is clear that both fires are significantly harder to identify using radar when compared to those of Black Saturday and the Anglesea basin.

Due to the unavailability of polarimetric data from these radars, analysis in the difference between co-polarisation, cross-polarisation and in the differential phase cannot be undertaken. It is clear that existing weather radars in Australia possess the capability to detect smoke plumes in a qualitative means, and indeed support those observations made by literature. These observations further indicate that typical smoke plumes fuelled by native biomass within Australia are highly reflective within the microwave region of the electromagnetic spectrum.
Chapter 2 - Literature Review

2.5 Research Questions and Methodology

2.5.1 Research Questions

Large ash particles, which are the remaining solid constituents of cell structures from biomass, are noted within published literature as one of the primary causes of scatter created from smoke plumes. This assumption has arisen from observations of the linear depolarisation ratio \((LDR)\) and other scattering coefficients made of polarimetric and circular polarised radar measurements \([34, 38, 44, 45, 54, 55, 64-66]\).

If ash particles are a major contributor to the overall scatter of smoke plumes, there are a number of research questions that arise involving the current body of knowledge. These questions must be answered in order to adequately understand the fundamental scattering characteristics. This will in turn both validate and improve inverse scattering models to quantify and analyse radar data of smoke plumes in a more coherent manner.

The research questions to be investigated in this dissertation include:-

- Important to the scattering of dispersed mediums such as ash particles, is the analysis of their geometric properties and concentration. How do these changes with fire conditions and various tree and plant species?

- Based on the current knowledge of ash particles inside smoke plumes, little is known about their RF material properties \([34, 38, 44, 45, 54, 55, 64-66]\). Does the relative complex permittivity change with different plant and tree species commonly found within bush and forested areas? If so, how?

- In reference to the existing body of knowledge of radar observations made of smoke plumes; none have analysed the scattering effects of vegetation found within the Australasia continent \([43, 49]\).
• Due to the complexity of fires, a number of other effects must be considered in relation to the physical properties of ash particulates. How do the RF material properties change with fire temperature and moisture content? As larger ash particles are suspected to contribute significantly to the overall scatter, do different exposure temperatures have any effect on the shape and size of ash particles?

• The RF material properties and shape of the particles play an important role in determining the intensity of a reflected field. In observations made by polarimetric and circular polarised radar, measurements of polarimetric coefficients have shown that the particles are orientated horizontally and are mostly needle-like in shape [34, 38, 44, 45, 54, 55, 64-66]. Is this observation isolated to the type of biomass being burnt or is it typical of the dynamic behaviour of ash particles, regardless of their shape?

• The behaviour of the particles has also shown to comply with coherent particle scatter which must also be investigated [64-66]. This may have significant consequences when analysing wideband, high frequency systems. On the fundamental level is coherent particles scatter present over a wide range of frequencies?
2.5.2 Methodology for Research

To study these research questions, a number of fundamental areas relating to the propagation of electromagnetic waves within a volume of space containing ash particulates must be considered. The scattering from dispersed targets as defined by Eqn. (67), outlined in Appendix A, is dependent on the radar cross-section and also the polarisation of a transmitted and received electromagnetic wave. So what exactly does the RCS represent on a fundamental level?

The RCS describes the ratio between the scattered powers from the target(s) to that of the total power of the incident field. Looking at the total radar cross-section as defined by Eqn. (67) the total scattering is the reflectivity of dispersed targets by the scattering volume being observed. The scattering volume as discussed is ultimately dictated by the far-field pattern of the radars antenna while the volume scatter is dependent on the number of particles presented within that volumetric cell. These two components are represented graphically in Fig. 7.

![Graphical representation of the total radar cross-section containing the contributions of the volumetric radar cross-section of each particle contained within a resolute scattering volume.](image)

The radar reflectivity ($\eta$) of a number of dispersed targets generally depends on a number of physical and electromagnetic properties. The reflectivity is the result of three constituents relating to the concentration/volume fraction of particles within a scattering volume, the radar cross-section ($\sigma_i$) of each particle and the scattering from different polarised electromagnetic waves. The polarisation as explained can be linear or circular polarised. Due to the common implementation of polarimetric radar measurements, only linear polarized electromagnetic
waves will be considered within this dissertation. This includes both co and cross polarisation field vectors as defined in Eqn. (60) in Appendix A. These three components relating to the radar reflectivity are dissected graphically in Fig. 8.

![Diagram showing concentration/volume fraction, polarization, and scattering](image)

**Fig. 8 – Roadmap for understanding the scattering characteristics of solid ash particulates.**

For ash particles, three areas must be analysed to provide a complete picture of the total scatter field. These three primary areas are the ‘geometric’, ‘dynamic’ and ‘electromagnetic material’ properties of ash, which enable a study of ash on a macroscopic level. An outline of these properties can be observed in Fig. 9.

Under the geometric heading, there are two sub-properties which need investigating. The first relates to the volumetric properties of the particles such as their surface area, cross-section and thickness/diameter, all required to describe the physical space the material occupies. The second is the shape of the particles, which includes properties such as their aspect ratio and shape type. The aspect ratio is required to describe their elongation, while the shape type represents the baseline shape of the particles (i.e. plate/disk-like, sphere-like, cylinder/needle-like, etc). Finally, the exposed temperature of the originating biomass must be considered, such that its effects on the volumetric properties can be characterised.
Fig. 9 – Graphical representation of the different geometric, dynamic and electromagnetic properties required to characterise the radar cross-section of an individual ash particle. Included is the relative chapters and section where these properties have been analysed.

The next consideration is the dynamic properties of ash related to their behaviour within the atmosphere. This includes analysis of their common stability modes in both the ascent and descent phases, as well as their orientation relative to an incident propagating electromagnetic field. This area must also focus on fire dynamics and the interactions of thermally driven cycles carrying ash particles up and away inside a smoke plume. The dynamic behaviour of the particles in regions where the flow is dictated by fire/atmospheric interactions and those transitioning to purely atmospheric flow conditions must also be analysed.

The final consideration is the RF material properties, specifically the analysis of the effective relative complex permittivity and permeability. Here, the effects of exposed temperature on the mass and porosity of ash particles must be characterised. Coupled with this is the absorption of atmospheric moisture and what effects this has on the RF material properties of ash. Finally, an analysis of the base relative complex permittivity (ε<sub>base</sub>) of ash, represented by the permittivity of a non-porous ash sample, is also required. This information
is necessary to define mixing law models, which may then be used to analyse and simulate the scattering characteristics of multiple ash particulates. Again the effects of exposed temperature for the base permittivity must also be considered.

### 2.6 Conclusion

This chapter has outlined the literature relating to the evaluation of radar for remote sensing of fires. It has examined where radar currently fits in the scope of fire sensing technologies, whilst undertaking an in-depth analysis of literature relating to observation of smoke plumes. Available radar data for three different fires within Victoria, Australia have been analysed with relation to satellite imaging. All cases have illustrated good correlation for defining the location of fire activity and the size of a smoke plume. It has also been shown that radar detects scattering from plumes in the absence of pyro-cumulonimbus clouds and lack of precipitation. This has demonstrated that constituent mediums inside plumes can create sufficient scatter. Identifying particulate scatter as one of the many possible scattering sources, a breakdown of the research methodology was outlined. The geometric and dynamic properties of the ash will now be presented in Chapter 3.
Chapter 3 – Geometric and Dynamic Properties of Ash

3.1 Introduction

The RF scattering effects of fires, in particular those that are created from smoke plumes are extremely complex. The scattering ability of a volumetric target such as ash is determined by the total reflectivity of all particles within a finite volume of space. To better understand these scattering effects and to begin to answer some of the proposed research questions, this chapter will address the base material properties of ash. It will focus primarily on the geometric, dynamic and physical material properties that may have a direct effect on scattering characteristics. The knowledge gained within this chapter will provide a fundamental basis for understanding how ash acts as a physical material. From this foundation, the ensuing chapters will take a more in-depth look at RF material properties and the reflectivity ($\eta$) of ash over a wide range of frequencies.

A number of tree and plant species have been selected for analysis, with particular emphasis on what effects exposed temperature has on biomass structure, elemental composition, porosity, mass and volume. Furthermore, the dynamic behaviour of ash particles as they ascend into the atmosphere and then descend back towards the ground will also be analysed within this chapter.

In total, eight different tree and plant species have been analysed to varying degrees. Six of those species are native to Australasia, including three eucalypt species: the acacia, casuarina and pteridium. Due to their dense population within the Australian continent, the focus of this dissertation will fall largely on the messmate eucalypt (eucalyptus genus). Second to this is the blackwood wattle (acacia genus) which will also be explored. The remaining species include popular pinus and cupressus, used for soft wood plantations and wind breaks respectively. Various properties of these species will be used to compare the geometric, dynamic, physical and electromagnetic properties that differ significantly from the two primary species. A brief introduction to these genera will be given in the following
sections and information regarding the remaining species selected for reference only is outlined in Appendix B.

### 3.2 Tree/Plant Species Samples

An outline of the chosen plant and tree species to be sampled for their ash will be presented within this section. A visual record has also been made and used to predict the species of the various flora genera selected. It should be noted that without DNA testing, the exact sub-species type cannot be accurately determined.

Australia has a number of unique plant and tree species which are immensely diverse in their shape, size and natural ecosystem. The coastal areas of Australia, stretching along the east, south-east, and south-west coast are predominantly covered by forested areas. Moving inland towards central Australia, the landscape begins to change from woodlands to scrublands. The density of the vegetation around the country is closely linked to the amount of annual rainfall [98]. Areas of higher average rainfall provide more bush-like vegetation, while those of lower rainfall show more shrub-like vegetation. Also, large areas of grassland are also present amongst these regions, both naturally occurring and as a result of clearing for agricultural purposes.

Both bushfires and grass fires are of particular importance when it comes to actively monitoring fire threats. Both have very different behaviours which are a combination of their effective fuel density, potential energy stored within the fuel and susceptibility to drying. Grass fires for example, are known to spread extremely quickly and have been reported to move upwards of speeds greater than 40 m/min [99-102]. Bushfires on the other hand, are more complex. These types of fires generally have multi phases, including transitions between undergrowth to crowning fires. Depending on the severity, they also frequently cause spot fires significant distances from the main fire front. They are also harder to control due to the inaccessibility of forested areas [103, 104]. Remote sensing of bushfires is of particular importance within Australia for these reasons. Highly populated areas also exist within these forested areas and are of concern when it comes to protecting lives. The Black Saturday fires are just one example of the devastation that bushfires can cause within these communities [1]. To limit the scope of this dissertation, only bushfires have been considered.
3.2.1 Eucalyptus Genus

The Eucalyptus Genus is extremely common within Australia [105]. Its genus was first identified during the earliest explorations of Australia and has now grown to represent some 800-900 individual species [105, 106]. Eucalyptus has many commercial uses too. The species is harvested for fuel, oil, timber and wood chips for making paper. The extreme diversity of the genus also allows it to grow in both arid environments such as inner Australia while dominating most of the north, east and south coast areas where annual rainfall is present.

The success of the genus in the harsh Australian climate has been its ability to adapt to different growing climates. Regions of Australia with high density forest and large variations in sunlight have eucalyptus species with horizontally held dorsiventral leaves. For the harsher arid lands where large amounts of direct sunlight are present, species with more vertically held isobilateral leaves can be found. In most cases eucalypt species of similar type will vary only by the type of leaf [105, 106]. One of the key drivers for the intense fires in Australia is the flammability of eucalyptus leaves. The leaves are considered some of the most flammable vegetation types in the world [3, 4, 107, 108]. The location of the eucalyptus genus throughout Australia is illustrated in Fig. 10.

![Map of Australia showing the population of the Eucalyptus genus (blue dots) [106, 109]](image-url)
3.2.1.1 Messmate Eucalypt (Eucalyptus obliqua)

The Messmate Eucalypt is the primary tree species to be analysed within this dissertation. This species of eucalypt is most common throughout the hilly or mountainous areas of the south-eastern parts of Australia [106]. Geographically, it is extremely common in the lower latitudes of Victoria throughout the Alpine and Otway national parks. It is also found along the Great Dividing Range and heading north into southern New South Wales (NSW). The species also spreads south into Tasmania and west into South Australia. The species can grow up to nine metres in height, however; this can vary based on localised growing climates.

The messmate eucalypt can grow in a wide variety of soils, which makes it adaptable to a wider variety of growing conditions. A population map for the messmate eucalypt is illustrated Fig. 11 [105, 106]. The messmate leaves are slightly asymmetrical at the tips, with adult leaves being dark green and glossy. Juvenile leaves become oblique and are discoloured, generally shading into light reds and greens. These young leaves become darker in colour as the leaves mature over time. The bark of the messmate eucalypt is rough and fibrous, with branches that smooth out towards the tips [106]. Its fruit houses a large number of seeds and is slightly ovoid in shape, brown in colour and clumped in small groups of three to five pods. Features of the messmate eucalypt are illustrated in Appendix B.

![Geographical map of Australia showing the population of the Messmate Eucalypt (blue dots) (105, 106)](image)

As previously noted, the Messmate Eucalypt sub-species was selected for its widespread growth in Southern Victoria. In particular, it is extremely common within the Otway, Yarra

36
Rangers and Alpine national parks, which cover some of the largest natural reserves within the state of Victoria.

### 3.2.2 Acacia Genus

The Acacia genus, commonly known as the wattle, is widespread through Australia with six sub-genera and more than 300 different species [106]. After the eucalyptus genus, it is the second most common genus on the Australian continent. Acacia species vary immensely in size and shape, ranging from tall forest trees to low sprawling shrubs. The genus is best recognised by its spectacular flowering, which is distinctly yellow in colour and which can last for several weeks at a time. The genus can grow at the rapid rate of two metres in height per year for up to five years, with a life expectancy of anywhere between 25-50 years [106].

The leaves of the Acacia genus vary from species to species. They are typically found to be pinnate/bipinnate or phyllodes (thin and flat in shape), and along with their inflorescences are important for classifying each species. The bark of the species also varies, ranging from smooth to rough. Branches are relatively small, typically in the order of 20 mm or less [106]. The genus is a vital source of nitrogen in its natural ecosystem and is an important source of animal fodder. Most species will grow in regions of moderate rainfall ranging between 750 mm and 1500 mm per year. A population map of the Acacia genus within the Australian continent is illustrated in Fig. 12.

*Fig. 12 – Geographical map of Australia showing the population of the Acacia Genus (blue dots) [106, 109]*
3.2.2.1 Black/Blackwood Wattle (Acacia melanoxylon)

Black Wattle is typically found in south-eastern Australian in coastal regions. Its main growing region extends from South Australia, into Victoria and Tasmania and spreading as far north as Queensland. The species typically grows to a height ranging from six to ten metres with its main stem dominating this height range, especially within open forests [106].

Its bark is usually rough and dark brown/black and grey in colour. Younger trees have smoother, lighter coloured main stems with high tannin content [106, 109]. A population map of the black wattle tree is illustrated in Fig. 13. The foliage of the Black Wattle is bipinnate in nature, with dark green adult leaves. Examples of the Black Wattle tree collected for analysis are illustrated in Appendix B.

![Geographical map of Australia showing the population of the Blackwood Wattle (blue dots) [106, 109]](image-url)
3.3 Origins of Ash

During the combustion phase of organic plant and tree materials, various solid and gaseous phases are produced. These phases vary immensely in composition, with many of the compounds produced during the decomposition of the biomass rendered toxic to both animals and humans [76, 110-114]. Within the solid phase, three distinct particle distributions are found. These include prominent nucleation \((\text{particles } < 1 \, \mu\text{m})\), accumulation \((\text{particles between } 1 \, \mu\text{m and } 2 \, \mu\text{m})\) and coarse particle \((\text{particles } > 2 \, \mu\text{m in effective diameter})\) [76]. Within the prominent nucleation and accumulation lies what is generally termed smoke particles. These are typically spheroidal in shape and from a scattering perspective, are too small in known concentration to be a significant player in the overall scatter detectable by smoke plumes [68, 69, 76, 115].

Conversely, ash particles that fall within the coarse distribution category have unique geometric properties determined on the macroscopic level by the remnant cell structures of the originating biomass. These can be of sufficient size to create detectable scatter, however; this is completely dependent on their electromagnetic characteristics.

This section will explore the various methods and techniques for preparing and analysing fire ash. The ash samples have been analysed from two different sources, including ash created from small open fire tests and a designed linear burn chamber. Due to the unsafe nature of open fire tests, validation of the linear burn chamber performance with respect to creating statistically correct ash particles has been undertaken.

3.3.1 Properties of fires

The preparation of samples used to determine the geometric properties of ash as well as the relative complex permittivity and permeability requires some careful consideration. Indeed, samples required to determine geometric properties vary from those required to measure RF material properties. In both cases, controlled and uncontrolled specimens are required to gather a full understanding of the fundamental material properties.

Under the geometry heading of the proposed research map required for analysing the scattering properties of ash \((\text{illustrated in Fig. 9})\), the investigation of a particle’s surface area, thickness/radius, aspect ratio and shape must be carried out. As these properties represent actual physical properties of ash created from a fire, they can only be determined by
analysing uncontrolled samples. Due to the impracticalities of creating large fires specifically for the purpose of collecting ash, more practical methods need to be established.

The first step in analysing the origins of ash is to investigate how it is fundamentally created. This in turn provides a means for analysing and comparing safer alternatives to large-scale open fire tests. Furthermore, investigating how biomass burns under different fire conditions and the resultant ash provides invaluable information on the types of particles that are ejected into the atmosphere during a fire. In light of these considerations, three open fire experiments were planned. The experiments were designed to have almost identical burn conditions. Two physical parameters, which help to define the intensity of a fire, relate to what is termed the fuel loading factor (\( F_l \)) and the degree of cure (\( \text{DoC} \)). The fuel loading factor relates to the amount of biomass present per unit area. For the purpose of analysing the effects of the fuel loading factor on the properties of a fire, the biomass can simply be weighed and placed evenly within a specified area. The degree of curing relates to the amount of moisture present within the biomass. As water requires a significant amount of energy to change its physical state (i.e. liquid to gas), a lower degree of curing results in a more efficient burning of the biomass. The degree of curing can be determined using two methods: the first and most common approach is to weigh biomass samples before and after dehydrating them inside an oven at low temperatures. The difference in weight gives the degree of cure for the biomass. The second method involves placing the biomass samples inside a vacuum chamber at low pressure. The vacuum chamber allows for the water content to boil off and thus be removed. The vacuum chamber was found to provide exceptional results over the oven dehydration method however it can only be used on existing dried biomass samples. Both the fuel loading factor and degree of curing are defined using Eqns. (1) and Eqn. (2).

\[
F_l = \frac{m_w}{A} \left( \frac{kg}{m^2} \right)
\]

(1)

\[
\text{DoC} = \left( 1 - \left( \frac{m_w - m_d}{m_d} \right) \right) \% 
\]

(2)

Where \( m_w \) is the mass of the ‘wet’ biomass to be burnt, \( m_d \) is the dry mass of the biomass void of moisture (kg) and \( A \) is the fuel area (\( m^2 \)).
3.3.1.1 Open Fire Experiments

Messmate eucalypt biomass was selected for analysis within the three open fire tests. Naturally forming ground litter was collected and weighed to define specific fuel loading factors of $F_i = 1$, 2 and 3. Samples of the collected biomass were also taken and used to calculate the degree of curing (DoC). To test how the eucalypt biomass burns and to study how ash is formed within open fires, a correlation between the material properties of ash and the peak flame temperatures must be made. Typically, flame temperature is used to help define the amount of energy being released by a fire. The flame temperature also plays an important role in driving the thermodynamic/atmospheric interactions and thus the probable ejection heights of ash into the atmosphere [51, 52, 116].

The experimental setup consisted of weighed biomass which was placed on top of a 2 mm thick stainless steel base plate. A steel post was positioned in the centre of the base plate and used to house four, 3 mm k-type thermocouples as illustrated in Fig. 14. Each thermocouple was spaced 40 mm apart, with the first thermocouple positioned 70 mm from the stainless steel base plate.

![Illustration of the experimental setup use for measuring the temperature of small open fires using eucalypt biomass.](image)

Fig. 14 – Illustration of the experimental setup use for measuring the temperature of small open fires using eucalypt biomass.

The k-type thermocouples were connected to a Terran Engineering 4-channel USB thermocouple data logger. Each channel reading a single k-type thermocouple was checked against a calibrated Anritsu temperature metre. The data logger can produce an accuracy of 1°C, at a sampling speed of 10Hz. K-type thermocouples typically consist of a fused, bi-metal junction covered by a metal jacket. This metal jacket, which is typically made of stainless
steel or similar alloy, has a less than unity emissivity ($\varepsilon = 0.9-0.95$). This causes the thermocouples to reflect some of the thermal radiation. For this reason, the measured temperatures from the data logger must be corrected to obtain correct flame temperature readings. Using multiple thermocouples also helps to improve the correction of the temperature measurements. The correction procedure used for the thermocouples is further outlined in [117, 118].

The biomass was spread evenly over an approximate area of 500 mm x 500 mm (length x width). The properties of the three open fires have been outlined in Table 2. Both the mass of the eucalypt biomass being burnt and the remaining ash were measured. The difference in mass between the two measurements was then used to calculate a quantitative representation of the total mass of both the solid and gas phases released into the atmosphere. Ambient atmospheric temperature and relative humidity remained consistent for all tests, while the recorded average wind velocity was less than one metre per second (m/s). This was the lower limit for the anemometer used to measure the wind speed. Visual records of the wind speed were made by observing the velocity of the smoke column. Here, it was estimated that the wind velocity was within the approximate range of 0.4-0.6 m/s. Maximum wind gusts were measured to be between 1.1 m/s and 1.5 m/s.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fuel (kg)</th>
<th>Ash (kg)</th>
<th>Loss (% w/w)</th>
<th>DoC (%)</th>
<th>$F_l$ (kg/m²)</th>
<th>Temp (°C)</th>
<th>RH (%)</th>
<th>$V_{wind}$ (m/s)</th>
<th>$V_{gust}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus 0.25</td>
<td>0.075</td>
<td>70</td>
<td>~6</td>
<td>1</td>
<td>22</td>
<td>35</td>
<td>&gt;1</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus 0.5</td>
<td>0.123</td>
<td>75.4</td>
<td>~6</td>
<td>2</td>
<td>21.1</td>
<td>34</td>
<td>&gt;1</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus 0.75</td>
<td>0.165</td>
<td>78</td>
<td>~6</td>
<td>3</td>
<td>20.9</td>
<td>34</td>
<td>&gt;1</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

The resultant corrected temperature plots for the three fires at different fuel loads are illustrated in Fig. 15, Fig. 16 and Fig. 17 respectively. The channel colours represents one of the four thermocouple reading outlined in Fig. 14. The second peak displayed in Fig. 18 was the result of fire re-ignition/flare-up.

It is clearly demonstrated by these temperature plots that an increase in the fuel loading factor results in an increase in the peak flame temperature. This is a direct result of the increase in available fuel, which translates to the amount of energy available per unit area. To analyse any possible correlation or disassociation between these two parameters (flame temperature and material properties), a quantitative visual analysis of the remaining ash produced from fires can be made, with the consistency of the ash indicating probable
scattering sources. Using the last of the three open fire tests, where \( F_1 = 3 \), an illustration of the fire during its initial burn stage is illustrated in Fig. 18. The ash remaining after the fire was close to being extinguished, as illustrated in Fig. 19.

Fig. 19 illustrates large inconsistencies in the colour of the ash. The lighter coloured ash represents areas where almost complete combustion was obtained, while the darker regions represent areas of incomplete combustion. The resultant ash for the open fire test, where \( F_1 = 2 \), is illustrated in Fig. 20. Comparing the two images of the remaining ash, it is shown that the lower temperatures achieved during the second open test causes an increase in the amount of biomass which intern causes less of the biomass to reach a fully combustible state.

---

*Fig. 15 – Temperature profile of a 0.5 m x 0.5 m fire with a fuel loading factor of 1 kg/m².*
Fig. 16 – Temperature profile of a 0.5 m x 0.5 m fire with a fuel loading factor of 2 kg/m².

Fig. 17 – Temperature profile of a 0.5 m x 0.5 m fire with a fuel loading factor of 3 kg/m².
Visually, it is clear that the types of ash being produced from fires are extremely complex. As the scattering of the ash is important with regards to radar, knowing the exact properties of the particles is of greatest concern. It is shown from both Fig. 19 and Fig. 20, that the assumed notion that there is a direct link between the material properties of ash and a fire’s flame temperature does not hold completely true. Qualitatively however, it is shown in Fig. 19 and Fig. 20 that for identical burn conditions, larger fuel loading factors produce more ash which has a higher effective exposed temperature.

The next step is to investigate those particles that are termed flying ash. These particles represent those ejected into the atmosphere by the thermodynamic cycle. To examine these particles created for these small fires, a collection frame was built and positioned around an open fire to collect falling ash. The frame was designed to collect larger particles, which fall closer to the fire source. The frame was made from black cotton fabric that was stitched into a large square, covering some 11 m² in surface area. In the centre of the collection frame, a 1 m² cut out was removed to allow the biomass to burn without affecting the cotton structure. A rendered illustration of the completed collection frame with relation to the fire burn volume is illustrated in Fig. 21. Initial testing was carried out using a slightly altered arrangement, whereby the collection frame was simply laid out flat on the ground.

*Fig. 18 – Example of the open fire test with F₁ = 3*
Fig. 19 – Results of the ash generated from the open fire test with $F_l = 3$

Fig. 20 – Results of the ash generated from the open fire test with $F_l = 2$
The final arrangement was lifted using support posts and tilted to help collect more of the flying ash. Once again, the fire contained eucalypt ground litter with a fuel loading factor of $F_l = 14$. The increase was required to generate a sufficiently large thermal updraft to carry the flying ash away from the fire. An illustration of the initial fire tests can be observed in Fig. 22. The ejection of embers and particles into the air can be observed in Fig. 22 c) and Fig. 22 d). The small particles were carried up by the thermal draft created by the fire and away by any slight breeze, where they then fell out along the direction of the wind.

The remaining ash not ejected into the atmosphere is illustrated in Fig. 22 f). A similarity between the collected flying ash and the ash remaining at the fire source can also be seen. This demonstrates that the burnt biomass within fires provide a potential pool of scattering sources. These sources are only released into the atmosphere under the correct thermodynamic conditions. Here, this is related to the particles mass and the force of the thermal updraft.

Examples of the ash captured on the collection frame are illustrated in Fig. 23. Due to the broad leaf structure of the eucalypt leaves, the resultant ash demonstrates a particularly high probability of plate-like structures. Finally, examples of larger ash particles (> 25 mm$^2$) carried outside of the collection area are illustrated in Fig. 24. The size, shape and even colour are similar to the bulk of the high temperature ash remaining at the fire source. The inconsistency of the ash material is again highlighted in Fig. 24 with some of the particles showing evidence of dark, carbonaceous regions. To analyse the ash on a more quantitative level statistical probability distribution functions (PDF’s) can be measured about each of their different geometric properties. To achieve this for large populations of particles image processing techniques can be implemented.
Chapter 3 – Geometric and Dynamic Properties of Ash

Fig. 21 – Rendered illustrations of the open fire particle collection frame. Side view illustrates the thermodynamic principle of how the particles are lifted into the atmosphere then fall out onto the collection frame.
Fig. 22 – Small open fire test with particle capture frame. a) heaped eucalyptus biomass in centre of frame, b) Heap size relative to 30cm ruler, c) initial burning with particle on collection frame, d) illustration of embers being ejected from fire, e) completion of the open fire test and f) example of the remaining ash.
Fig. 23 – Illustrations of the variability of particle collected on the frame of the open fire tests. Particles then taken and image processed to work out geometric distributions
Fig. 24 – Examples of large flying ash deposited up to 2m away from the collection frame of the open fire tests.
3.4 Image Processing Results for Open Fire Tests

Using the ash which landed onto the collection frame of the open fire tests described in section 3.3, image processing (see Appendix C) can be employed to generate statistical distribution functions about the particles. Due to the plate-like structure of the eucalyptus ash, the projected area and aspect ratio give a good indication of the expected particle geometry. The last requirement, being the thickness/radius of the particles will need to be measured and will be presented under section 3.6.2 of this chapter in more detail.

Due to the fragile nature of ash particles, images were taken using a Digital Single-Lens Reflex (DSLR) camera. The results from the image processing method for the estimation of the surface area and aspect ratio of the open fire particles are illustrated in Fig. 25 and Fig. 26 respectively.

The aspect ratio is measured by fitting an ellipse to each ash particle. Here, the major and minor axis of the ellipse are calculated and the aspect ratio determined by Eqn. (3).

\[
AR = \frac{\text{minor axis length}}{\text{major axis length}}
\]

(3)

The surface area of the particles shows illustrated in Fig. 25 a clear exponential distribution, increasing towards particles of smaller surface area. The distribution is fitted with a generalised pareto (GP) PDF, representing the exponential increase towards these smaller particles. This type of distribution is reasonable as the number of smaller ash and smoke particles will understandably be greater in frequency than those of larger size. The coefficients that describe the log-logistic distribution are expressed in Fig. 25.

The aspect ratio shows a slightly different story, with the majority of particles having a slightly asymmetrical ratio. This feature is important when examining the types of scatter these particles may produce. Asymmetric properties may have an effect on the polarizability of a scattered electric field and thus the effects require further investigation. Similarly, the distribution is fitted with a PDF. Here a generalised extreme value (GEV) distribution has been fitted due to the asymmetry of the particles’ aspect ratio. The corresponding coefficients for the GEV distribution are illustrated in Fig. 26. Full descriptions of the PDF functions used within this dissertation are found within Appendix A.
Fig. 25 – Projected surface area of 4133 particles collected from a number of the open fire tests. Results analysed using Image processing. Distribution fitted with a generalized pareto PDF with $k = -0.38$, $\sigma = 1.50$, $\theta = 0$.

Fig. 26 – Aspect ratio of 4133 particles collected from a number of the open fire tests. Results analysed using Image processing. Distribution fitted with a generalized extreme value (GEV) PDF with $k = -0.335$, $\sigma = 0.19$, $\mu = 0.489$.
3.5 Alternative Methods for Creating Ash

To replicate an open fire in a contained environment, a number of methods were investigated. The first and simplest technique for preparing ash is placing biomass inside a heated oven. This method has high temperature accuracy, however; the resultant ash has very little variability and resemblance to ash particles created in natural fires. Recent advancements made in fire research by the CSIRO has resulted in the development of the CSIRO Pyrotron [119]. The pyrotron is a 26.5m long wind tunnel with a 2 m x 2 m x 4.8 m burn volume. The wind tunnel is specifically designed to study fire under controlled environmental conditions.

The ability to control atmospheric conditions, specifically wind speeds is a favourable quality. Coupled with this is the ability to sample biomass with variable curing factors and fuel loading factors. This allows for the study and control over the intensity of a fire and thus its flame temperature. The large size of a pyrotron style wind tunnel for the purpose of creating ash for determining their scattering characteristics is not required. This is because the study of ash particles and their electromagnetic properties only need to represent the possible solid matter released within a smoke plume. Fire behaviour such a spread rate for example can be neglected as it is has little bearing on the possible particle scatter once they have been released into the atmosphere. Furthermore, the conditions in which ash particles are created are extremely difficult to quantify. Difficulties arise from uncertainties in the combustion process undertaken by an individual particle as it travels from its originating biomass into the atmosphere. This means that the effective exposed temperature of particles may not be entirely dependent on traditionally measured quantities of fires such as flame temperature, temperature profiles and/or total energy release. This is further evident through observations made of the ash colour, as illustrated in the open fire tests (see Fig. 23 and Fig. 24). Here, the ash particles vary immensely in colour, fluctuating between different shades of grey. The darker or blacker regions of a particle suggest incomplete combustion of volatiles from the biomass. However, the same fire can also produce light grey particles with little variation in colour.

Using similar principles to those outlined for the CSIRO pyrotron, a linear burn chamber was designed and built for generating ash. As the purpose of this chamber is to generate ash particles and not to study fire behaviour, the chamber can be significantly shortened. The chamber design was based around three 120 mm fans which were driven via a variable speed
control. The biomass is heaped within the chamber and can be ignited externally via a high temperature propane flame. The chamber incorporates PC data logged thermocouples to measure flame temperature. Finally, the flying ash is collected with a series of mesh screens located at the exit of the chamber. The mesh consists of a 1mm x 1mm metal weave. Ash that is small enough to pass through the mesh screens is then collected on an aluminium plate. An outline of the chamber is illustrated in Fig. 27.

The characterisation of the axial velocity within the chamber section was carried out using an anemometer. The axial velocity was measured at one hundred locations within the chamber. The velocity is only representative of the velocity along the axial direction. The anemometer does not measure velocity in other directions and so does not take into consideration effects such as swirling, which is caused by the fans. The maximum mean air velocity within the burn section of the chamber is 1.44 m/s. This can be changed using the variable speed controller. Velocity slices at three horizontal height locations have been measured within the chamber and are illustrated in Fig. 28. These provide an indication of the localised air velocities within the chamber. The non-uniformity of the velocity flow within the chamber is a direct result of induced swirl created from the three fans. This however does not affect the performance of the chamber for the purpose of creating ash.

Similar to the open fire tests, four thermocouples installed in the wall of the chamber were used to measure the flame temperature of the biomass. The high temperature k-type thermocouples were again corrected for the emissivity ($\varepsilon$) of the stainless steel jackets (see [117, 118]).
Fig. 27 – 3D illustration of the burn chamber developed for generating ash particles.
Fig. 28 – Measured and 3D interpolated linear velocity (m/s) along the axial length of the burn chamber, shown is slices of the velocity at a) 25 mm, b) 100 mm and c) 185 mm in the Z-dimension. Colour bar correlates measured wind speed within the chamber (m/s).
Fig. 29 – Examples of a) the types of biomass placed inside the burn chamber, b) the resultant ash caught on mesh screens and c) scanned images of ash particles pre-processed to remove background information and noise.
Examples of typical eucalyptus biomass used within the chamber and the resultant ash after the combustion process are illustrated in Fig. 29. The ash created within the chamber is seen to have similar geometrical properties to that generated within the open fire tests. Particle colour is also similar to that created from the open fire tests.

The respective flame temperatures measured using the thermocouples in the side wall of the chamber for three fuel loading factors are illustrated in Fig. 30 to Fig. 32. Measurements of flame temperature were taken at the chamber’s maximum air velocity. This demonstrates the ability to alter the flame temperature of the biomass using both the air velocity and fuel loading factor. This results in the ability to control the fire condition within the chamber and finally, the state of the ash particles to be collected on the mesh screens.

![Flame temperature measurements](image.png)

*Fig. 30 – Flame temperature measurements form thermocouples within the burn chamber based on a fuel loading factor of \( f_i = 1 \). Max air velocity \( V_{ave} = 1.44 \text{ m/s} \), Atm.Temp. 22 °C, RH = 35%*
Fig. 31 – Flame temperature measurements form thermocouples within the burn chamber based on a fuel loading factor of \( f_t = 2 \). Max air velocity \( V_{\text{ave}} = 1.44 \text{ m/s} \), ATM.Temp. 23 °C, RH = 37%.

Fig. 32 – Flame temperature measurements form thermocouples within the burn chamber based on a fuel loading factor of \( f_t = 4 \). Max air velocity \( V_{\text{ave}} = 1.44 \text{ m/s} \), ATM.Temp. 21 °C, RH = 37%.
3.6 Geometric Properties of Ash Particles

The analysis of the geometric properties of ash particulates will be examined within this section, along with the projected area, aspect ratio, thickness and particle shape. Validation of the burn chamber results will be considered and related to the open fire results measured in section 3.5.

3.6.1 Particle Projected Area Distributions

Using the burn chamber and the image processing techniques outlined in Appendix C, the analysis of the projected area of ash has been extracted for the messmate eucalypt and black wattle. The measured projected area distributions are illustrated in Fig. 33 and Fig. 34 respectively. Ash collected from the chamber that has been used for all statistical distributions within this chapter was restricted to a general case where the peak flame temperature was maintained within the range of 800 – 900 ºC. This was achieved by altering both the air velocity and fuel loading factor for the different plant and tree species tested. Based on the limitations of the scanning equipment, the minimum particle area has been restricted to particles ≥0.20mm². This area has also been chosen as it represents the crossing point from where the through thickness dimensions become equal to the cross-section dimensions.

When considering the messmate ash generated from the burn chamber in Fig. 33, an excellent statistical correlation to those particles found within the small open fire tests can be observed (see Fig. 25). It should be noted that image processing of the DSLR photos will incur slight skewing due to the perspective angle of the image. With this in mind, the overall variations in distributions are negligible. This provides the first confirmation criteria for validating the burn chamber for creating statistically correct ash.

The projected surface area distributions measured for both species can be seen to have slight variances. The messmate eucalypt shows a slight spreading in the projected area of the particles when compared to the black wattle. This is most likely due to the larger dorsiventral leaves of the messmate eucalypt. The leaves of black wattle are much smaller in cross-sectional area, thus restricting the development of these larger particles within fires.
Fig. 33 – Projected area distributions for messmate eucalypt ash particles ≥0.20mm² with a fitted generalized pareto distribution $k = 0.7215, \sigma = 1.1326, \theta = 0$

Fig. 34 – Projected area distributions for blackwood wattle ash particles ≥0.20mm² with a fitted generalized pareto distribution $k = 0.5063, \sigma = 0.7832, \theta = 0$
The extension of the area PDF into the micron range has been illustrated by Radke et. al. [69, 115]. Measuring the concentration of particles from a number of large files, three distant particle size distributions have been identified by Radke et. al. These particles (D~1-2µm) are however, too small to cause significant scatter at the measured concentrations and can therefore be ignored for the statistical distributions required to describe radar backscattering.

### 3.6.2 Particle Aspect Ratio Distributions

Although the projected area of an ash particle gives some indication of a particle’s size, it does not provide a complete picture as to the shape of the particle. The shape of a particle is important as it informs two factors relating to its scatter: its dynamic behaviour and scattering ability. A key indicator in distinguishing the various ash particle shapes created from different plant and tree species is the aspect ratio (see Eqn. (3)).

Due to the highly asymmetric shape of ash, the extraction of a particle’s aspect ratio is preferred over the commonly defined axial ratio for spheroidal-shaped particles such as those found in precipitation. The two aspect ratio distributions for the messmate eucalypt and black wattle are illustrated in Fig. 35 and Fig. 36 respectively. The aspect ratio shows excellent correlation to a GEV PDF distribution. There is excellent correlation between the aspect ratio and a GEV PDF distribution.

As illustrated, the variations in the aspect ratio distribution between the messmate eucalypt and black wattle are small. This is due to the broadleaf foliage structure being common to both species. Beyond these species, similar aspect ratio distributions have been measured for different eucalypt species. These will be summarised at the conclusion of this section.

When considering the messmate eucalypt distributions, the mean aspect ratio is slightly shifted compared to those observed in the open fire tests (see Fig. 26). The small shift in the mode of the distributions can be explained by the use of DSLR images instead of a scanning type arrangement.
Fig. 35 – Aspect ratio distribution for messmate eucalypt ash with fitted generalized extreme value distribution
\( k = -0.4175, \sigma = 0.1957, \mu = 0.543 \)

Fig. 36 – Aspect ratio distribution for blackwood wattle ash with fitted generalized extreme value distribution
\( k = -0.3758, \sigma = 0.1893, \mu = 0.5238 \)
Chapter 3 – Geometric and Dynamic Properties of Ash

Here, an optical error occurs within the open fires tests due to the relative perspective viewing angles of the images. As a result, the aspect ratio of the ash is stretched in one direction more than the other, causing a direct increase in the mode aspect ratio value. With little variance in the projected surface area and with acceptable differences in the aspect ratio, it has been shown that the linear burn chamber provides a valid means for generating and studying ash in a safe manner.

3.6.3 Particle Thickness/Cross-Section Distributions

The final geometric identifier for ash is the through thickness dimension. As the dimension cannot be directly measured using image-processing techniques, a manual measurement of each ash particle must be carried out. This however, presents a number of challenges; the most significant of which relates to establishing a method that does not cause any damage to the fragile ash particles.

To find an appropriate measurement technique, it can be assumed that the thickness of an ash particle closely represents the thickness of its originating biomass. To test the validity of this assumption, an analysis of changes in the particles’ cross-sectional thickness was carried out.

Using the measurement technique of micro-computer-tomography (Micro-CT), the through-thickness of biomass can be analysed. This technique uses the X-Ray transmission properties of samples over a 180º rotation to re-construct cross-sections of a sample. Examples of Micro-CT scans taken of the messmate eucalypt biomass exposed to various temperatures are depicted in Fig. 37.

As illustrated, the thickness of the biomass remains consistent up to an exposed temperature of 300 ºC. Beyond this point, the structure of the biomass shows some signs of warping, however; the thickness remains relatively consistent. This is not the case for cross-sectional dimensions representing the projected area of the particles. As is illustrated by Fig. 38, clear reductions in the projected area with respect to the exposed temperature can be seen. This has been quantitatively analysed using image processing and is illustrated in Fig. 39. Here, the reduction in area follows an exponential trend until the 450 ºC temperature point, where the projected area begins to show signs of stabilising. The rapid reduction in the cross-sectional dimensions demonstrates a consistent inward pull created by the remaining cell structures within the biomass.
Fig. 37 – Micro-CT scans illustrating changes to the cross sectional thickness of messmate eucalypt leaves exposed to temperatures (from top to bottom): a) dry, b) 150 °C, c) 200 °C, d) 250 °C, e) 300 °C, f) 350 °C, g) 400 °C. NOTE: Each image is a CT-scan taken from a different leaf structure.

Fig. 38 – Changes in the projected area of messmate eucalypt leaves exposed to temperatures (from left to right): a) dry, b) 150°C, c) 200°C, d) 250°C, e) 300°C, f) 350°C, g) 400°C. All samples were originally punched into 6.1mm disk, then exposed to each temperature range on a hotplate.
This inward pull helps to maintain the cross-sectional thickness of the particles, further supporting the assumption given for the through thickness dimension.

The notable changes in the cell structures illustrated in Fig. 37 occur primarily in regions where large population of spongy mesophyll cells exist. However, the bulk of material that is being removed from the biomass occurs in the leaves’ vein structures. This will be analysed in greater detail in section 3.7.4.

The validity of the assumption that the thickness of the biomass remains close to that of the originating biomass should also be valid for most if not all other plant and tree species. This thickness dimension is typically small compared to the cross-section dimensions making up the projected area.

Measurements of the thickness distribution of the messmate eucalypt and black wattle are illustrated in Fig. 40 and Fig. 41 respectively. The average thickness was measured from a number of dried leaf samples collected from numerous trees. Both species have been fitted with normal distributions for the thickness dimension and show a good fitting to this distribution for the limited samples measured. The average thickness of the wattle leaves is shown to be slightly higher than those of the messmate eucalypt. Furthermore, the spread of the distributions is larger for the wattle tree compared to the messmate.

Fig. 39 – Reduction in the projected area of eucalypt biomass at various temperatures. Reduction in area follows a similar trend to the normalised mass loss of the eucalypt species.
Chapter 3 – Geometric and Dynamic Properties of Ash

Fig. 40 – Thickness distribution for Messmate Eucalypt ash with fitted normal distribution, $\sigma = 0.0394$, $\mu = 0.2668$

Fig. 41 – Thickness distribution for Blackwood wattle ash with fitted normal distribution, $\sigma = 0.0804$, $\mu = 0.3036$
3.6.4 Particle Geometry Relative to Tree/Plant Species (Shape Type)

In the natural environment, complex structures are readily found. When it comes to the cellular level of biomass, these structures become extremely diverse. The general structure of ash in its complex form cannot be practically implemented to solve its scattering effects. Thus, a simplified geometric representation of the bulk shape of the ash must be established. To give an idea of the complex structure present within biomass, SEM images of various structures have been illustrated in Fig. 42. The three examples demonstrate the complex hair structures found on the underside of the bracken fern, the complex cell wall structure of a small eucalypt tree and finally, the extremely unusual shape of a cypress needle. To solve a generalised shape for these particles, the relative wavelength must be factored into the scattering model. In most cases, wavelengths are much larger than the physical size of ash particles, therefore finer geometric details have little bearing on the total scatter. Many electromagnetic problems are resolved by the implementation of a geometric assumption. A typical example relating to the successful implementation of geometric assumptions can be found in many precipitation models. Here, spheroidal geometries are assumed. In the case of ash, the high asymmetry of the particles leads to a case where the assumption of a spheroidal approximation is no longer valid. For this reason, further geometric assumptions about the particle’s shape need to be defined.

To analyse the different shapes of ash, there are two main sizing categories that need to be explored. The first grouping is of particles that can be defined as large. These particles provide significant scatter and have been classified here to be ash particles with a projected area greater than 0.2 mm$^2$. As previously stated, this lower limit is due to the restrictions of the scanning equipment used in the image processing methods and the crossing point for when the through thickness dimensions equal that of the cross-sectional dimensions from many ash particles. The second category is comprised of ash particles that are smaller than 0.2 mm$^2$. Particles within this size range have been statistically classified by Radke et. al. [69, 115]. To illustrate the complexities in the geometries of ash in both these ranges and to classify their geometric shapes, examples will be presented within this section.
Fig. 42 – Examples of a) under side of the bracken fern foliage, b) cell structure of a messmate eucalypt branch and c) external shape of a dried cypress needle
3.6.4.1 Shape of Ash ≥0.2 mm²

The complex structures of ash, resultant of the complex structures found in biomass, provide the fundamental building blocks for determining their underlying geometric shapes. In many cases, the formation of ash can be classed into three main geometric shapes: plate-like, needle/cylindrical-like and spheroidal-like. For observations of scattering from larger ash particles, spheroidal-like structures are less prominent. These are however, most prominent when analysing ash within the micron region. To better understand the shape that ash assumes, large-scale illustrations of particles collected for image processing have been presented in Fig. 43 to Fig. 48.

Fig. 43 – Examples of large messmate eucalypt ash particles showing their planar type geometries
Fig. 44 – Examples of large blackwood wattle ash particles showing their planar type geometries

Fig. 45 – Examples of large bracken fern ash particles showing their planar type geometries
Fig. 46 – Examples of large Sheoak ash particles showing their needle type geometries

Fig. 47 – Examples of large Sheoak ash particles showing their needle type geometries
Chapter 3 – Geometric and Dynamic Properties of Ash

The scanned images of ash shown within Fig. 43 to Fig. 48 illustrate the diversity of ash particles and their geometric shapes. Similarities are found between the messmate eucalypt and black wattle samples. Here, the ash produced from both species shows particles of planar geometry. These are tightly bound by the composition of their originating leaf structures. Complex planar geometries will contribute to the overall scatter of ash for example in planar particles as they have increased directional reflectivity when wavelengths are reduced. The scattering will then become highly influenced by the dynamic behaviour of the ash structures once ejected into the atmosphere. The dynamic behaviour of ash particles will be further explored in section 3.8.

The bracken fern sample illustrated in Fig. 45 is also of the planar-type geometry. Unique to the bracken fern are the small, pinnate leaf structures seen to subsequently present in some of the ash particles. Moving away from planar-type ash structures, the needle-shaped foliage of the sheoak, pine and cypress results in ash that may be represented by cylindrical-shaped geometry. These types of ash particles are well adapted for generalisation using spheroidal-like models such as oblate of prolate geometries. The radiata pine cross-section is similar to a half-cylindrical structure, to be discussed further in section 3.6.5.

Fig. 48 – Examples of large laylandii cypress ash particles showing their needle type geometries
3.6.4.2 Shape of Ash <0.2 mm²

Within the smaller particle size category, the effects of cell structure on the shape of particles are more profound. SEM scans of ash created from the six species examined within this dissertation are illustrated in Fig. 49 to Fig. 54. The general shape of these particles becomes more spheroidal in these smaller ranges, however; the abundance of small, planar-like particles are also still present. These structures are best illustrated by the bracken fern ash for example (see Fig. 51), where the layers between the cell structures have broken away. It is known from research carried out by Radke et. al. [69, 115] that smoke particles below 2 μm in cross-sectional length are extremely spheroidal in shape. The spheroidal-shaped particles are represented within Fig. 49 to Fig. 54 by the more lightly shaded particles. The lighter shade in the SEM images represents a low conductive medium. Here, with the exception of bracken fern, these spheroidal particles are mainly composed of calcium, which is the main element used in the formation of many plant cell structures. Bracken fern differs as it has a mostly silicon-based cell structure, resulting in its significantly contrasting combustion properties. The elemental composition of ash will be further discussed in section 3.7.2. This is highlighted by differences in the RGB and LAB colour models at different temperature ranges (see Appendix D) and the state of its large and small ash shown in Fig. 45 and Fig. 51 respectively. The differences between these smaller smoke particles and the smaller ash particles created from the remnant cell structures offer an excellent comparison between the two types of particles. In this larger range, the geometry of the particles begins to play a key role in the scattering properties of ash.
Fig. 49 – SEM image of typical small ash particles created from the a high temperature eucalypt sample (1000-1100 °C)

Fig. 50 – SEM image of typical small ash particles created from the a moderate temperature blackwood wattle sample (800-900 °C)
Fig. 51 – SEM image of typical small ash particles created from the moderate temperature bracken fern sample (800-900 °C)

Fig. 52 – SEM image of typical small ash particles created from the moderate temperature sheoak sample (800-900 °C)
Fig. 53 – SEM image of typical small ash particles created from the a moderate temperature radiate pine sample (800-900 °C)

Fig. 54 – SEM image of typical small ash particles created from the a moderate temperature cypress sample (800-900 °C)
3.6.5 Surface and Through Thickness Geometry

To complement the through thickness distributions outlined in section 3.6.3, a review of the through thickness shape of biomass will be explored. As shown in section 3.6.4, the shapes of large ash particles are very well characterised by their originating biomass structures. The aforementioned complexities in the biomass require a geometric assumption to be made for the through thickness dimensions of ash. Fig. 55 outlines different cross-sections and surface finishes of each of five different plant and tree species analysed. An illustration of the cypress needle can be observed in Fig. 42 c). Illustrated in Fig. 55 a) and Fig. 55 b) respectively are the cross-section views of the eucalypt and wattle. The effects of temperature on the thickness of the eucalypt has previously been detailed in section 3.6.3, however; it has been included here to help distinguish it from the other plant and tree species to be analysed.

As illustrated, the eucalypt and black wattle show very similar thickness cross-sections. This almost planar-type width is common for many broadleaf plant and tree species with the most variance seen in regions of veins and stems. The surfaces of both are also similar to stomata pores found covering the leaf. Here, the eucalypt is shown to have larger pores, thus resulting in its rougher surface texture.

The leaves of the bracken fern with their highly formed pinnate structures have a slight ‘C’ shaped cross-section as presented in Fig. 55 c). The edges of the leaf structure are folded, housing sorus spores used in the plant’s reproductive cycle [106]. The bracken fern’s surface structure is lumpy and textured, however may still be classed as a planar structure. It should be noted that the surface texture is significantly larger than that found in the eucalypt and wattle species.

Moving away from the planar cross-section in the eucalypt, wattle and bracken ferns, cylindrical cross-section can now be seen in the sheoak and pine species (see Fig. 55 d) and Fig. 55 c) respectively). The sheoak has a very well defined circular cross-section. Its surface has small, lengthways ripples that track its entire circumference. Conversely, the pine has a mushroom-shaped cross-section. This can be assumed to closely represent that of a semicircle, as the small indentations are insignificant when compared to typical radar operating frequencies. The pine’s surface is quite smooth, with a number of small stomata pores found running lengthways along the needles.
Fig. 55 – Cross-sectional and surface SEM scans of (a) messmate Eucalypt leaf, (b) blackwood wattle leaf, (c) radiata pine needle, (d) Bracken fern leaf and (e) Sheoak needle respectively
Fig. 55 (cont.) – Cross-sectional and surface SEM scans of a) messmate eucalypt leaf, b) blackwood wattle leaf, c) radiata pine needle, d) Bracken fern leaf and e) Sheoak needle respectively
3.6.6 Summary of PDF Functions for Ash

A summary of the PDF’s measured for a number of plant and tree species can be observed in Table 3. The importance of measuring these distributions is illustrated by the large variation between the geometric properties of ash created from different plant and tree species.

The area distributions for example illustrated similarities between species of similar sized foliage. This is clearly illustrated between the Blackwood wattle, iron bark and spotted gum species. Illustrations of their similarities in projected area foliage can be seen in Appendix B. This further bolsters the hypothesis that the area distribution is relative to the size and shape of the originating biomass. The aspect ratio distributions on the other hand exhibit similarities between all planar-type particles and needled-type particles. The exception here is bracken fern, which has small, complex, pinnate leaf structures with a high individual aspect ratio. It is likely that there is a correlation between the sizes of the foliage being consumed, the respective projected area and aspect ratio of the ash particles. This however, requires further investigation using a large number of specimens.
<table>
<thead>
<tr>
<th>Name</th>
<th>Shape Type</th>
<th>Area (GP)</th>
<th>AR (GEV)</th>
<th>Thickness/Diameter (Normal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Messmate</td>
<td>Planar</td>
<td>$k = 0.7215, \sigma = 1.1326, \theta = 0$</td>
<td>$k = -0.4175, \sigma = 0.1957, \mu = 0.5430$</td>
<td>$\sigma = 0.0394, \mu = 0.2668$</td>
</tr>
<tr>
<td>Blackwood</td>
<td>Planar</td>
<td>$k = 0.5063, \sigma = 0.7832, \theta = 0$</td>
<td>$k = -0.3758, \sigma = 0.1893, \mu = 0.5238$</td>
<td>$\sigma = 0.0804, \mu = 0.3036$</td>
</tr>
<tr>
<td>Wattle</td>
<td>Planar</td>
<td>$k = 0.4727, \sigma = 0.9049, \theta = 0$</td>
<td>$k = -0.4424, \sigma = 0.2053, \mu = 0.5407$</td>
<td>$\sigma = 0.0333, \mu = 0.2396$</td>
</tr>
<tr>
<td>Iron Bark</td>
<td>Planar</td>
<td>$k = 0.4727, \sigma = 0.9049, \theta = 0$</td>
<td>$k = -0.4424, \sigma = 0.2053, \mu = 0.5407$</td>
<td>$\sigma = 0.0333, \mu = 0.2396$</td>
</tr>
<tr>
<td>Spotted Gum</td>
<td>Planar</td>
<td>$k = 0.4459, \sigma = 0.7662, \theta = 0$</td>
<td>$k = -0.4681, \sigma = 0.2034, \mu = 0.5631$</td>
<td>$\sigma = 0.0269, \mu = 0.2218$</td>
</tr>
<tr>
<td>Bracken Fern</td>
<td>Planar</td>
<td>$k = 0.6399, \sigma = 1.6956, \theta = 0$</td>
<td>$k = -0.2753, \sigma = 0.2007, \mu = 0.3912$</td>
<td>$\sigma = 0.0829, \mu = 0.4121$</td>
</tr>
<tr>
<td>Sheoak</td>
<td>Cylindrical</td>
<td>$k = 0.5965, \sigma = 1.0824, \theta = 0$</td>
<td>$k = -0.01847, \sigma = 0.1712, \mu = 0.3046$</td>
<td>$\sigma = 0.2312, \mu = 1.0564$</td>
</tr>
<tr>
<td>Radiata Pine</td>
<td>Half -</td>
<td>$k = 0.1997, \sigma = 0.6877, \theta = 0$</td>
<td>$k = -0.05322, \sigma = 0.1660, \mu = 0.3160$</td>
<td>$\sigma = 0.2247, \mu = 1.0416$</td>
</tr>
<tr>
<td></td>
<td>Cylindrical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leylandii Cypress</td>
<td>Cylindrical</td>
<td>$k = 0.1151, \sigma = 1.0159, \theta = 0$</td>
<td>$k = -0.2934, \sigma = 0.1826, \mu = 0.4519$</td>
<td>$\sigma = 0.2184, \mu = 1.0326$</td>
</tr>
</tbody>
</table>
3.7 Physical Material Properties of Biomass and Ash

Although the geometric properties of ash play a significant role in determining their scattering characteristics, the underlying physical behaviour of biomass aids in overall scattering ability. This section investigates those properties of ash (as a material) that are affected by temperature. It will investigate the effective mass reduction of biomass over different exposed temperatures, and examine macroscopic changes to the cell structure of biomass, elemental composition and finally, moisture absorption rates.

3.7.1 Effects of Temperature on Organic Materials

One of the most profound effects temperature has on naturally occurring organic materials is the decomposition of its base material. This decomposition in the case of biomass from tree and plants species causes a direct synthesis of many biogenic, toxic and carbonic compounds [75, 113, 114, 120]. Concerning the scattering characteristics of the remaining solid constituents of ash, the effects of porosity play a direct role in altering the relative complex permittivity. In a basic sense, this can be explained by considering that the amount of material present within a finite unit volume. As the porosity increases there is less physical material to interact with an electric field. This lower amount of interaction by definition must decrease in a permittivity of a material. By mapping the effects exposed temperature has on the mass of various tree and plant species, a better understanding of the relative complex permittivity of ash can is ascertained (see chapter 4). This can be carried out by measuring the biomass before and after the samples are heated to a specific temperature. Here, two considerations must be made: what is the most appropriate heating system and what is the time required for the biomass to stabilise in its mass at each temperature range?

For the analysis of the eucalypt and wattle samples, low temperature measurements to 400 °C using a temperature-controlled hotplate were found to be most successful. Here, single leaves were heated at any one in the middle of the hotplate where reduced thermal gradient effects were then imposed on the samples. The temperature directly under the heated leaf samples was monitored with an external k-type thermocouple. Temperatures were stabilised to an accuracy of ±1 °C and were not allowed to increase above this error limit for each of the designated temperatures to be measured. Temperature ranges chosen included an un-burnt sample, and heated samples from 150 to 400 °C with 50 °C increments. As temperatures
increase, so too does the challenge of maintaining a steady heat source. For temperature ranges above 400 °C, a heated kiln oven (rated to 1200 °C) was utilised, however; the temperature control in the oven lagged significantly due to the refractory ceramic tiles that insulate the heating elements. Here, the reading error of the k-type thermocouple was again ±1°C, however; the stability often drifted 15 °C above the imposed temperature range. These deviations are unavoidable as the PID control units will naturally over-ramp the temperature once the oven door has been opened and the samples placed inside. This is the result of the lag time between the heating elements and the thermocouple.

The second issue connected to the holding time required to heat the samples. This must be characterised as samples will have different mass the longer they remain within the oven. This has been measured up to 400 °C for the messmate eucalypt and is illustrated in Fig. 56. Here, the mass of the eucalypt biomass stabilises after holding each sample at the required temperature for approximately ten minutes. This however, is the lower limit and should be well exceeded when preparing samples.

![Fig. 56](image)

Fig. 56 – Time required for messmate eucalyptus leaves to stabilise in mass when exposed to different temperatures.

This is especially true at those temperatures above 450 °C where the biomass begins to ember. At this stage the biomass is left to stabilise until all the embers have burnt out. Once
the samples have completed their heating cycle they are placed directly onto scales to measure their mass. This is required to minimise the effects of moisture absorption within the material and to give a true representation of the amount of physical mass lost.

Applying the required baking times to the three eucalypt and black wattle samples, the resultant normalised mass loss can be tracked. To determine the normalised mass loss, dried biomass was measured before and after temperature exposure. The change in the mass can then be used to define the normalised mass loss \( m_{\text{loss}} \) using Eqn. (4). Where \( m_d \) is the dry mass of the biomass be for heating and \( m_t \) is the mass after heating at temperature.

\[
m_{\text{loss}} = \frac{m_d - m_t}{m_d} \times 100 \text{ (\%)}
\]

The resultant normalised mass loss for all four biomass samples is illustrated in Fig. 57. Resultant mass loss between the four samples is shown to be identical once the stabilisation time has been satisfied. Although these results to 400 °C are identical for the species measured, this may not be true for all tree and plant species. Especially those cell structures made of silicon that differs from the mostly calcium-based cell structures (as will be discussed further in 3.7.2).

Fig. 57 – Normalised mass loss of different biomass up to 400 °C. MM - Messmate Eucalypt, SG – Spotted Gum, IB – Iron Bark, BW – Blackwood Wattle, m - measured data and f- fitted cubic extrapolation
Due to strong similarity in the normalised mass loss curve of the eucalypt and wattle species, it is highly probable that both will follow identical trends at much higher temperatures. To analyse the effect of the normalised mass loss on biomass, the messmate model has been extended to 600 °C, after the expulsion of almost all of its volatile compounds. An illustration of this extended normalised mass model is demonstrated in Fig. 58.

![Figure 58 - Normalised mass loss of the messmate eucalypt biomass over various temperature ranges.](image)

As illustrated in Fig. 58, a sharp decrease in the biomass is seen at approximately 450 °C, representing the ember point (when there is sufficient energy to allow the biomass to fully decompose). Soon after reaching this temperature, the biomass attains its flash and ignition points where the volatile carbonic compounds begin to vaporise and promote flame propagation. Beyond this flaming point when the majority of the original mass has been removed, the remaining cell wall structures hold a relatively constant mass.

A significant change in the normalised mass loss is seen to occur at approximately 250 °C. This temperature represents the transition point for many of the carbonic compounds, which subsequently begin to decompose at a rapid rate.
The effects of the reduction in the mass shown in Fig. 58 gives a clearer picture of the trend expected for the relative complex permittivity. As explained previously, this is because there is less physical material interacting with a propagating electric field. This leads to the conclusion that the permittivity of the biomass for the eucalypt and wattle species should follow a similar trend. If so, it is highly likely that many other tree and plant species will exhibit similar material behaviour.

3.7.2 SEM-EDX Elemental Analysis

The relative complex permittivity is defined as a macroscopic material property which describes the displacement of an electric field within a medium. As it deals with the interaction of an electric field on a macroscopic level it is heavily weighted by the composition and porosity of physical material bound within a volume of space. In the case of biomass, there are a number of interesting elemental trends with respect to exposed temperature which can be measured to provide a better understanding of changes in the relative complex permittivity. These will be measured and analysed in Chapter 4.

Particular focus is drawn to changes in elemental carbon and oxygen within the biomass. These two elements form the basic building blocks for all organic life on earth. Carbon is known to be an extremely lossy material. It is commonly used in many microwave applications such as RF absorbers [94]. Even small quantities of lossy carbon present within a material can cause the material to have a high large relative complex permittivity due to its localised conductive properties.

Using an analysis technique called Energy-Dispersive X-Ray spectroscopy or EDX, the elemental composition by percentage weight of ash samples can be extracted. The EDX here has been carried out in a FEI Quanta 200 Environmental Scanning Electron Microscope (ESEM). Sample preparation is critical when using the EDX method. Measured samples must be planar, and non-charging to allow for the best penetration of an X-ray beam into the biomass. Using flat broadleaf structures helps with this requirement. Fine ash must be carbon coated to reduce charging and this small concentration removed from the final analysis result. To improve sensitivity all samples measured were done so using an average amp. time of 100 μs. The resultant EDX scans for a messmate and blackwood wattle sample up to 400 °C are illustrated in Fig. 59 and Fig. 60 respectively.
Chapter 3 – Geometric and Dynamic Properties of Ash

Fig. 59 – SEM-EDX measurement of the concentration by weight and elemental breakdown of messmate eucalypts leaves versus temperature

Fig. 60 – SEM-EDX measurement of the concentration by weight and elemental breakdown of blackwood wattle leaves versus temperature
To maintain a control in the EDX results, a consistent reference area in each of the biomass samples was scanned at each exposed temperature range. Like the normalised mass curves outlined in section 3.7.1, the carbon and oxygen concentration up to 400 °C shows a consistent trend. Here, elemental carbon is shown to follow an exponential downwards trend as the concentration of elemental oxygen increases. Other trace elements are shown to be of negligible concentrations within this temperature span. This said, the temperature window here is quite small and so it is important to describe this elemental breakdown at higher temperatures.

Increasing the exposed temperature of the biomass into higher temperature ranges (> 800 °C), the EDX samples need further preparation. At these temperatures the ash begins to charge due to the consistent X-Ray interactions. This charging will directly affect the accuracy of the EDX elemental analysis. To combat this charging problem the samples were coated in carbon before EDX was carried out. A comparison between the elemental breakdowns for an un-burnt sample, equivalent 400 °C, 800 °C (blackwood wattle) and 1000 °C (messmate eucalypt) are illustrated in Table 4 and Table 5 respectively. Particular focus has been given to the concentration of silica and calcium at these higher temperatures. These two elements are major nutrient minerals required for all plant and tree life ash they are required for building cell structures [121, 122]. As shown in the two tables, the concentration of calcium rises substantially in both samples and the amount of silica also varies. Here the messmate ash sample is shown to have a significantly low silica concentration to that of the Blackwood wattle.

<table>
<thead>
<tr>
<th>Element</th>
<th>Name</th>
<th>Wt. (%) un-burnt</th>
<th>Wt. (%) at 400°C</th>
<th>Wt. (%) at 1000°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Carbon</td>
<td>86.45</td>
<td>67.21</td>
<td>12.98</td>
</tr>
<tr>
<td>O</td>
<td>Oxygen</td>
<td>12.70</td>
<td>24.66</td>
<td>41.36</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
<td>0.10</td>
<td>0.17</td>
<td>3.84</td>
</tr>
<tr>
<td>Ca</td>
<td>Calcium</td>
<td>0.04</td>
<td>2.68</td>
<td>27.52</td>
</tr>
</tbody>
</table>

*Composition determined using SEM EDX, amp. time = 100μs.*
Quantified amounts of calcium and silica in other plant and tree species exposed to high temperatures are illustrated in Table 6. The composition of this ash reveals a similar trend showing the removal of carbonaceous compounds from the biomass samples. During elevated temperatures, all samples measured show a gradual increase in oxides, most likely in the form of calcium oxide. The remaining carbon may also be transformed into calcium carbonate. Once these reactive carbonaceous compounds are removed, the remaining cell structures are primarily composed of elemental calcium and/or silica. As the mass of the ash is known to stabilise at around 450-500 °C this elemental composition shown in Table 6 will represent the elements interacting with an electric field. This will form what is known as the base relative complex permittivity of ash and will be explored in chapter 4.
3.7.3 Moisture Absorption Rates

The absorption of moisture from the surrounding atmosphere occurs in many different materials. Ash, being a highly porous and hygroscopic material, is no exception [115]. The absorption of moisture into an ash particle has two main effects relating to its physical and scattering properties. Firstly, there is an increase in the particle’s weight. This has a direct effect on the inertial properties and thus the probable life of the particle within the atmosphere. The extreme end of this is if the ash reaches super-saturation, where it will effectively act as a water droplet [68, 69, 123]. If this occurs, observations of the polarisation of a scattering field will trend more towards spheroidal (oblate or prolate) shaped particles, showing close correlations in the differential reflectivity and linear depolarisation ratio. In the limited polarimetric observations of smoke columns, this is shown not to be the case [44, 54, 55]. At low altitudes, super-saturation is less likely to occur, as most atmospheric conditions do not promote the formation of condensing water vapour [124]. This is a different case at higher altitudes, especially with the formation of large pyro-cumulonimbus clouds [50]. However, it has been shown that significant scatter is still present at lower altitudes, suggesting that particle-based scattering and clear-air scattering may be present [38, 94].

Naturally, a particle will still readily absorb moisture. The rate of absorption for the eucalypt biomass exposed to various temperatures has been measured and is illustrated in Fig. 61. This leads to the second outcome: the gradual change in the relative complex permittivity with increased moisture absorption. Illustrated in Fig. 61, the absorption of moisture by weight shows clear changes with respect to the maximum exposed temperature of the biomass. At lower exposed temperatures the rate of absorption is also lower, whilst the time to saturation is prolonged. The opposite effect occurs for those particles exposed to higher temperatures. These absorption rates can again be explained by the rapid reduction in the mass of the particles with temperature, as is illustrated in Fig. 58. As particles lose mass at an exponential rate through the combustion process, the effective porosity must also increase proportionally. As the porosity increases, cell structures still widely intact at lower temperatures begin to break down and become more readily exposed to the atmosphere.
This in turn causes an effective increase in the relative surface area exposed to the atmosphere, thus increasing the absorption rate of moisture into the ash. Moisture absorption during the first few minutes of a particle’s life in the atmosphere shows low relative absorption by weight. This however, changes in the presence of high humidity and rain. An abundance of water is found in all living biomass and dead ground litter. Ground litter will generally hold a small amount of moisture depending on the time of year, rain fall and weather. This is typically analysed by measuring the degree of cure (DoC see section 3.3.1). Natural biomass in the form of living branches, leaves, undergrowth plants and grasses will also contribute significant amounts of moisture to the atmosphere. In the case of trees, the burning of their leaves for example will mainly occur in large fires or crowning fires.

The steam released from the combustion process will naturally condense as it begins to cool down in the upper atmosphere. Smoke particles in the micron size are known to be cloud condensation nuclei (CCN) which act as condensation points [68, 69]. These particles can become super saturated and form rain droplets however in the presence of high particulate concentrations the required saturation levels may not be reached.
Chapter 3 – Geometric and Dynamic Properties of Ash

Fig. 62 – Time sequence demonstrating the rapid absorption of ash into a water droplet from capillary effects. (atm. temp. = 22°C, RH = 40%)
The likelihood supersaturated particles forming rain from a fire event is complex and depended on atmospheric conditions (temperature, humidity, and pressure), consumed fuel, moisture content and fire size. To demonstrate the extreme case where ash particles may interact with condensed water droplets, a time sequence of such interactions were observed using a high speed 240 fps video camera. This time sequence is illustrated in Fig. 62. The images show a droplet of approximately 3mm in diameter, representing 0.008ml of water and positioned on a plastic sheet.

The highly porous ash is then brought into contact with the water droplet. Due to the capillary action of water, the ash is rapidly pulled into the water droplet, forming an anisotropic medium. The entire process is complete in just 40 milliseconds. These effects may occur in nature when condensing water collides with larger ash particles, however; it is likely that the ash will act like a sponge, absorbing more than its weight in moisture.

### 3.7.4 Porosity, Density and Cell Structure with Respect to Temperature

When analysing the relative complex permittivity of a porous material, it is useful to determine the amount of physical material to that of air. This is commonly described as the volume fraction ($V_t$) or its inverse, the true porosity ($\phi_{true}$). The volume fraction is described by Eqn. (5) and the porosity by Eqn. (6).

\[
V_f = \frac{V_t}{V_l} = \frac{p_{bulk}}{\rho_{solid}}
\]  

\[
\phi_{true} = \frac{V_v}{V_l} = 1 - \frac{\rho_{bulk}}{\rho_{solid}}
\]

The importance of the volume fraction to the scattering comes into play when considering the amount of physical material interacting with an electric field. It also plays a role in defining the effective relative complex permittivity of the material. Calculating the bulk density of a leaf is quite easily achieved using a pycnometer type arrangement and is calculated as Eqn. (7).
\[ \rho_{\text{bulk}} = \frac{m_{\text{bulk}}}{V_{\text{bulk}}} \] (7)

The measured bulk density up to 400 °C and the extended model up to 600 °C of the messmate eucalypt are illustrated in Fig. 63. These measurements are again limited by the fragility of the particles, therefore only accurate measurements to 400 °C can be made. The bulk density is shown to closely follow the trend of the normalised mass loss curve.

The equivalent measured bulk density model values for a number of wattle leaves are illustrated in Fig. 64. The bulk density measurements of the wattle show very similar trends to that of the eucalypt model, (as illustrated by the dotted line in Fig. 64). Here, the wattle’s bulk density is shown to have a very similar that of the messmate eucalypt. Due to the similarities in the measured bulk density and normalised mass loss curves (as illustrated in Fig. 57), a reasonable prediction of the bulk density into the higher temperature ranges can be made.

![Graph showing bulk density vs temperature for messmate eucalypt leaves](image)

*Fig. 63 – Measured bulk density of messmate eucalypt leaves at up to 400 °C, model extended based on normalised mass loss curve from Fig. 58.*
Fig. 64 – Measured bulk density of Blackwood wattle leaves at up to 400 °C. Comparison of measured values against the average bulk density of the messmate eucalypt is shown by the dotted line.

Unlike bulk density, the solid density of a material is extremely difficult to measure due to its close cell structure. The solid density is affected by the atomic structure making up the biomass, including its molecular bonding and temperature. As demonstrated in section 3.7.2, carbon is the most highly concentrated element within the biomass. Amorphous carbon which best represents that found in biomass, is known to have a solid density of approximately 2.267 g/cm³ [125]. This gives an approximate baseline solid density value for most biomass structures. It should also be noted that the value of the solid density changes with respect to the exposed temperature of the biomass as it turns to ash. This is highlighted by the elemental composition illustrated in section 3.7.2.

To map the porosity or volume fraction with respect to temperature, solid density must be known and with good accuracy. To achieve this, a pycnometer type measurement method can be used. Here, a sample is submerged into water and the displaced volume is recorded. This however is dependent on the submerging liquid filling all the voids within the material. As the SEM images of ash in section 3.6.4 suggest, this has to be achieved on a sub-micron level to be accurate.
The measured solid density for ash made using a pycnometer type measurement for the different species can be referenced in Table 7.

<table>
<thead>
<tr>
<th>Sample</th>
<th>TEMP. RANGE (ºC)</th>
<th>$\rho_{\text{solid}}$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt</td>
<td>1000-1100</td>
<td>2.84</td>
</tr>
<tr>
<td>Wattle</td>
<td>800-900</td>
<td>2.01</td>
</tr>
<tr>
<td>Bracken Fern</td>
<td>800-900</td>
<td>1.95</td>
</tr>
<tr>
<td>Sheoak</td>
<td>800-900</td>
<td>2.95</td>
</tr>
<tr>
<td>Pine</td>
<td>800-900</td>
<td>2.11</td>
</tr>
<tr>
<td>Cypress</td>
<td>800-900</td>
<td>2.35</td>
</tr>
</tbody>
</table>

*Note: volume displacement measured at 22 °C where $\rho_{\text{water}} \approx$ 0.998 g/cm$^3$*

The measured density values are shown to vary with respect to each of the plant and tree species. Particular attention should be brought to the low solid density values of the bracken fern and wattle species. Here, remaining porosity within the ash is most likely due to slightly lower solid density values. The measured density values are on average similar to that of the amorphous carbon. It is highly probable that the solid densities for dry biomass, regardless of species, will be similar. This can be somewhat explained by the similarities found in the material properties of different plant and tree species with respect to temperature.

Due to the difficulty of measuring the solid density of biomass and thus determining its porosity, alternative techniques have also been investigated. Porosity can be measured directly using a Micro-Computer Tomography (MicroCT) technique. This involves using a high resolution X-Ray source and detector to produce transmission X-Ray images of a sample. Firstly, the sample is rotated 360 degrees perpendicular to the X-Ray source. The raw transmission images are then filtered and processed into vertical slices using a back projection technique. The reconstructed cross-section images represent an intensity map based on the absorption properties of a sample. The image sequence is then imported into Avizo (*a program by VSG*), where it is scaled based on the resolution of the MicroCT scans. Avizo then thresholds the images, reconstructing a 3D model. This process is identical to the image processing methods outlined in *Appendix C*, with the exception that information is extracted by integrating over the entire 3D image domain. This allows for the extraction of voxel (*volumetric pixel*) information to calculate porosity. The accuracy of this extraction method like all image processing methods is limited by the ability to apply an index grey
scale threshold. The voxels within the desired threshold range can then be used to extract the porosity data at the given resolution.

Due to high costs associated with this technique, only the eucalypt biomass was scanned using the MicroCT. The extracted porosity is illustrated in Fig. 65.

The porosity has been measured for three confined volumes of the biomass and an equivalent porosity for a large mapped volume. Equivalent cross-sectional MicroCT images demonstrating changes in the biomass cell structure due to temperature are shown in Fig. 66. With the given CT resolution of 2.18 μm, most of the cell wall structures are clearly visible after back projection. At temperatures below 250 °C, the structures of the messmate eucalypt show no significant signs of change. This is in accordance with observations made in the measurements of the normalised mass loss and through thickness. Noting that the biomass shrinks in size with increased temperature, the almost consistent porosity shown in Fig. 66 is correct. This being said, a significant amount of physical mass is still being lost from the biomass structure which cannot be explained by this shrinking effect alone. In these lower temperature ranges, only volatile gasses are released form the biomass. This indicates that the MicroCT scanner with its given scan resolution still does not have sufficient accuracy to determine porosity of the biomass structures. This error effectively makes cell structures
Chapter 3 – Geometric and Dynamic Properties of Ash

appear more solid than they actually are, therefore the porosity will be underestimated. In temperature ranges above 250 °C, significant changes in the cell structures are observable. As illustrated, density rapidly depletes in the vascular tissues. At 350 °C and 400 °C, almost no material is present in the vascular tissues while significant structural contraction is present. The spongy mesophyll cells (represented by the spaces between the vascular tissues) are also shown to also lose their form, thus aiding the contraction mechanism. Illustrated by the cell structure is the apparent contrast in densities over the entire leaf volume. This again highlights the complexities of biomass, especially when understanding how an electromagnetic field will interact on a macroscopic level. Porosity increases as the temperature approaches 400 °C and the contracting mechanism becomes less influential compared to the physical loss of material. Overall, the porosity does not show a significant variation (in the order of 10%) compared to the normalised mass loss. Here, it is shown that the eucalypt biomass will lose in the order of 60% of its total mass. It can be concluded that the contracting mechanism appears to balance porosity as material is removed. A full statistical analysis of the porosity is required in order to gain a better understanding of this exact interaction.

Taking the extracted porosity from the MicroCT technique a comparison can now be made to the expected porosity calculated using the bulk density of the measured samples. The extraction of the solid density can be made by Eqn. (6). A comparison between the different measurement techniques for eucalypt biomass is illustrated in Table 8. As seen, there is a divergence between the expected porosity (using Fig. 64.) and the porosity extracted using MicroCT. There is relatively good agreement at lower temperatures with the difference around 8% in the un-burnt sample. At higher temperatures this increases to 22%. Although the difference is large between these two methods both have a number of limitations. For example the measured porosity must assume a solid density value for each sample. The MicroCT technique on the other hand is limited by its resolution. Also, only one sample at each of the temperature points was examined at for the MicroCT technique. This does not give a complete statistical representation of the porosity at each temperature point. Analysing Fig. 64 further, the variation in the bulk density is significant and it is highly plausible as the samples measured using the MicroCT technique fall outside of the standard deviation at higher exposed temperatures. The only way to definitive know if this deviation is not within the statistical average is to measure a larger population using the MicroCT technique, however these approximations are sufficient.
Fig. 66 – Micro CT cross-section slices of messmate eucalypt leaves exposed to temperatures of a) unburnt, b) 150°C, c) 200°C, d) 250°C, e) 300°C, e) 350°C and f) 400°C. (scale bar represents a total length of 1500μm). (Measurements of messmate leaf samples courtesy of Dr. Benedicta Arhatari, Department of Physics, Latrobe University) Prepared at RMIT University
Fig. 66 (cont.) – Micro CT cross-section slices of messmate eucalypt leaves exposed to temperatures of a) unburnt, b) 150°C, c) 200°C, d) 250°C, e) 300°C, f) 350°C and g) 400°C, (scale bar represents 1500μm), (Measurements of messmate leaf samples courtesy of Dr. Benedicta Arhatari, Department of Physics, Latrobe University). Prepared at RMIT University

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>$\rho_{\text{bulk}}$ (g/cm$^3$)</th>
<th>$\rho_{\text{solid}}$ (g/cm$^3$)</th>
<th>$\Phi_{\text{EXPECTED}}$</th>
<th>$\Phi_{\text{MICROCT}}$</th>
<th>$\Delta \Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>0.829</td>
<td>2.267</td>
<td>~0.63</td>
<td>0.55</td>
<td>0.08</td>
</tr>
<tr>
<td>150</td>
<td>0.700</td>
<td>2.267</td>
<td>~0.69</td>
<td>0.54</td>
<td>0.15</td>
</tr>
<tr>
<td>200</td>
<td>0.662</td>
<td>2.267</td>
<td>~0.71</td>
<td>0.52</td>
<td>0.19</td>
</tr>
<tr>
<td>250</td>
<td>0.661</td>
<td>2.267</td>
<td>~0.71</td>
<td>0.52</td>
<td>0.19</td>
</tr>
<tr>
<td>300</td>
<td>0.487</td>
<td>2.267</td>
<td>~0.79</td>
<td>0.61</td>
<td>0.18</td>
</tr>
<tr>
<td>350</td>
<td>0.438</td>
<td>2.267</td>
<td>~0.81</td>
<td>0.66</td>
<td>0.15</td>
</tr>
<tr>
<td>400</td>
<td>0.393</td>
<td>2.267</td>
<td>~0.83</td>
<td>0.61</td>
<td>0.22</td>
</tr>
<tr>
<td>1000-1100</td>
<td>0.039</td>
<td>2.84</td>
<td>~0.99</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Note: volume displacement measured at 22°C where $\rho_{\text{water}} = 0.998$ g/cm$^3$*
3.8 Ash Particle Dynamics

3.8.1 Dynamics of Fires – Thermal and Fluidic

The thermodynamic process involved with the propagation of fires is primarily driven by the immense amount of thermal energy released during the decomposition of organic biomass. The broader interaction of fires with the atmosphere has a number of classical thermo-fluidic responses that intensify the combustion process. These effects are a coupling between fires and the atmosphere [51, 52, 116, 126]. The most prevalent and noticeable fluidic effects of fire-atmospheric interactions are vortices [51, 52, 116, 126-132]. Vortices are generally associated with large fires, however; the same thermo-fluidic processes are also present in small fires with less intensity and duration. Vortices formed in large fires are generally found in two orientations known as horizontal roll vortices and vertical roll vortices.

Horizontal roll vortices exist in three main formations: single vortices, double vortex pairs and transverse roll vortices [51, 52]. Formations of these horizontal roll vortices are illustrated in Fig. 67 to Fig. 69. The single horizontal vortex is a complex formation thought to develop in turbulent shear layers [52, 116]. As turbulent air flows through complex terrain, various objects can effectively split it into a horizontal vortex. Airflow then rolls and captures the fire, dragging smoke into a helix-type vortex. These types of horizontal vortices are reported to occur in very high wind speeds, upwards of 16-22 m/s [52].

Horizontal vortex pairs are created by boundary layer interactions between fluids of different densities. Here, the heat generated from fires reduces the density of the ambient air within the flaming region. This lower density air then rises to create a fluidic movement. As the air rises it begins to loop, creating vortex tubes that envelope those vortices already present. As a result, the surrounding vortex rings are rolled upwards so that the plume diverges and forms counter rotating vortex pairs [116, 129].

Finally, transverse vortices are created by buoyantly heated air rising above circular-shaped fires. As the heated air rises, it creates a donut-shaped, counter-rotating ring with the cooler atmospheric air. These vortices can break up in the presence of strong winds creating partial rings on one face of a fire front.

Both the horizontal vortex pairs and the transverse vortices are reported to be formed in the presence of low wind speeds in the order of 6m/s or less [52].
Fig. 67 – Illustration of a single horizontal vortex, blue arrows represents air vectors forming the vortex and red arrows represent ambient wind condition and direction of fire.

Fig. 68 – Illustration of a horizontal vortex pairs, blue arrows represents air vectors forming the vortex and red arrows represent ambient wind condition and direction of fire.
Vertical roll vortices are generally associated with whirlwinds or fire tornados [116, 130, 131]. These vortices occur when transverse winds meet and begin to rotate. These can be created by natural boundaries such as rocks, mountain ridges and tree lines. The dynamics of fires outlined above will play a large role in the scattering ability of ash particles.

As the ash particle transition into the atmosphere (ascent phase) they will be move based on the fluidic influences the thermal dynamic cycles have on the atmosphere. Similarly the particles will also descend from the atmosphere under different atmospheric conditions. The dynamic behaviours of the particles under these there two flight phases will be examined further in section 3.8.2.
3.8.2 Particle Dynamics in Ascent and Descent Phase

The dynamic behaviour modes of ash particles travelling through the air contribute significantly to the total scatter. This is however, only observable when considering polarised electromagnetic fields. In the case of planar particles such as those produced from eucalyptus biomass, the polarisation of the incident and scattering fields is particularly applicable. Clear distinctions for example, can be made between meteorological planar particles such as snowflakes and ice crystals, to spheroidal particles such as rain precipitation. In the case of ash, its structure has been shown to represent that of the originating biomass. With regards to ash created from the foliage of differing tree and plan species, changes in its scattering behaviour should also be detectable. As previously shown in this chapter, ash particles conform to two main geometric types: cylindrical and planar. Indeed, it is possible to characterise the dynamic properties of ash based on a representative sample for each geometric grouping. Here, messmate eucalypt ash will be used to represent planar geometries, while radiata pine will be used to represent cylindrical geometries.
The dynamic behaviour of planar-type particles conforms to two primary dynamic modes, represented as fluttering and tumbling [133-137]. The fluttering mode is that most commonly associated with falling leaves, whereby particles rock side to side as they descend. As the particles fall, both planar surfaces remain facing the same relative direction. In the tumbling mode, particles fall in the direction of motion. Here, the planar surfaces flip sides numerous times as particles descend through the atmosphere. Because the particles ascend and descend in 3-dimensional space, each with six possible degrees of freedom (*three translations, three rotations*), there is also the introduction of spin. This is represented by a corkscrew action as the particles move through space.

To study the extent of these different modes with regards to the behaviour of ash particles, image processing of high-speed video data was carried out. Both the ascent and descent phases were explored using ash from the messmate eucalypt. Along with a visual observation of the dynamic behaviour, an estimation of the Reynolds number was also conducted. The Reynolds number is a dimensionless coefficient representing the ratio of the inertial forces of the particles to the viscous forces of the fluid through which they travel.

When comparing particles, it is crucial that the Reynolds numbers are similar. One definition of the Reynolds number (\(Re\)) is given by Eqn. (8) [133-137].

\[
Re = \frac{aU}{v}
\]  

(8)

Where ‘\(a\)’ is the semi-major axis length of a particle, ‘\(U\)’ is the average transitional velocity and ‘\(v\)’ is the kinematic viscosity.

To capture the dynamic behaviour of ash particles in the ascent and descent phases, a slow motion video can be integrated with image processing techniques. The dynamic behaviour of particles in the descent phase can simply be captured by dispersing particles from a height and observing their natural falling behaviour using a 240 fps video camera. A similar arrangement in the ascent phase can also be used but in this case, particles are blown upwards using a small fan.

Converting the captured footage to individual frames, the average transitional velocity, particle semi-major axis and dynamic modes can be determined using ImageJ. Trajectory plots for eight particles showing examples of the different dynamic modes are illustrated in Fig. 71.
The first two particles represented as ‘P1’ and ‘P2’ are those particles in the descent phase, conveying a tumbling motion. Also observed is the high rate of spin present within these particles as they descend through the atmosphere. The next four particles represented as ‘P3’, ‘P4’, ‘P5’ and ‘P6’ illustrate the fluttering mode. This mode is most prevalent during the descent phase. In a study of over two thousand particles using slow motion footage, the fluttering mode was 5.7 times more active when compared to the tumbling mode in steady fall conditions. Similar dynamic modes are predominant in falling snowflakes, however; ash particles are less stable due to their highly irregular shapes.

Finally, ‘P7’ and ‘P8’ present the trajectory of the particles in the ascent phase. Here, the particles show more chaotic or random motion due to the direction and velocity of the air through which they travel. Observations also show a tendency for the broadside of the particle to align with the air velocity vector. An example of this behaviour has been illustrated in Fig. 71.

![Graph](image)

**Fig. 71 – Measured trajectory plots for a number of messmate eucalyptus ash particles showing the development of both the fluttering and tumbling modes in the descent phases, and stable chaotic mode during the ascent phase. Each horizontal bar represents the semi-major axis of each particle and a time step of approximately 8ms. T = Tumbling, F = Fluttering, C = Stable Chaotic, A = Ascent and D = Descent**

This observation may suggest that if particles travel within a column of sufficient air velocity, a higher than normal distribution of particles may be align with their broadside face perpendicular to the direction of the rising column. Similar effects are also seen where high winds are present. All aerodynamic properties of a particle are listed in Table 9. Particles of similar Reynolds numbers have been select to help compare the dynamics behaviours.
Table 9: Fluidic properties of Eucalypt Ash particles

<table>
<thead>
<tr>
<th>No.</th>
<th>a (mm)</th>
<th>( \rho_f ) (kg/m³)</th>
<th>( v^+ \times 10^{-5} ) (m²/s)</th>
<th>U (m/s)</th>
<th>Re</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>9.40</td>
<td>1.197</td>
<td>1.529</td>
<td>0.633</td>
<td>389.15</td>
<td>T,D</td>
</tr>
<tr>
<td>P2</td>
<td>3.41</td>
<td>1.197</td>
<td>1.529</td>
<td>0.632</td>
<td>140.95</td>
<td>T,D</td>
</tr>
<tr>
<td>P3</td>
<td>4.13</td>
<td>1.197</td>
<td>1.529</td>
<td>0.551</td>
<td>148.86</td>
<td>F,D</td>
</tr>
<tr>
<td>P4</td>
<td>9.94</td>
<td>1.197</td>
<td>1.529</td>
<td>0.515</td>
<td>334.50</td>
<td>F,D</td>
</tr>
<tr>
<td>P5</td>
<td>2.80</td>
<td>1.197</td>
<td>1.529</td>
<td>0.386</td>
<td>70.70</td>
<td>F,D</td>
</tr>
<tr>
<td>P6</td>
<td>3.61</td>
<td>1.197</td>
<td>1.529</td>
<td>0.374</td>
<td>88.22</td>
<td>F,D</td>
</tr>
<tr>
<td>P7</td>
<td>5.39</td>
<td>1.197</td>
<td>1.529</td>
<td>2.069</td>
<td>729.83</td>
<td>C,A</td>
</tr>
<tr>
<td>P8</td>
<td>5.86</td>
<td>1.197</td>
<td>1.529</td>
<td>0.877</td>
<td>336.29</td>
<td>C,A</td>
</tr>
</tbody>
</table>

+ Atm. Temp = 22.0°C, RH = 42%, \( b \approx 0.27 \text{mm} \)

T = Tumbling, F = Fluttering, C = Stable Chaotic, D = Descending, A = Accenting

For those particles portraying both the fluttering and tumbling modes in the descent phase, the incident angle of a propagating electromagnetic wave will have a dramatic effect on the principle scattering field. If radar is observing these particles at low grazing angles and at large ranges, they will effectively appear as horizontally orientated, needle-like structures. This may explain why polarimetric measurements have observed such structures inside smoke columns [44, 45, 55]. In contrast, vertically pointing radar will observe a significantly larger, broadside cross-section of the ash particles. The measured orientation angle PDF relative to the horizontal axis for the fluttering mode is illustrated in Fig. 72.

This distribution shows a standard deviation of 31.98 degrees for the eucalypt ash particles in this descent phase. This relatively large standard deviation means that planar particles displaying the fluttering mode will produce less coherent scatter at any given point in time. This scatter still favours a vertical pointing arrangement, however; an increase in scattering produced from higher elevation angles should also be noted. The data was collated by tracking the relative angle of the particles within the high-speed video stream. This is assumed to be equal in both orientation planes and portrays a significantly larger standard deviation than that reported for planar meteorological particles such as snowflake structures [138]. This higher distribution is most likely due to the high level of asymmetry within the ash particles.
The equivalent analysis for the radiata pine is illustrated in Fig. 74, Table 10 and Fig. 75. The cylindrically shaped pine ash particles only display two dynamic modes, namely fluttering and chaotic. The tumbling mode is not present in these cylindrically shaped particles. This is because they are stable about their horizontal axis. The major difference between the planar eucalypt and radiata pine ash particles is their flight stability. The cylindrical structures tend to remain in their original orientation for larger amounts of time, thus increasing the horizontal orientation distribution as illustrated in Fig. 75. In the random chaotic modes in the ascent phase, the particles again remain more horizontally aligned than their planar counterparts.

The relevance of these dynamic modes and their influence on scattering characteristics will be further analysed within Chapter 5. Particular attention will be given to planar-type particles and how their scattering is affected by these different dynamic modes. Large variations in the descent and ascent phases have been demonstrated in the case of planar ash particles.
Fig. 73 – Measured trajectory plots for a number of radiata pine ash particles showing the development of only the fluttering modes in the descent phases, and stable chaotic mode during the ascent phase. Each horizontal bar represents the semi-major axis of each particle and a time step of approximately 8ms. F = Fluttering, C = Stable Chaotic, A = Ascent and D = Descent

Table 10: Fluidic properties of Radiata Pine Ash particles

<table>
<thead>
<tr>
<th>No.</th>
<th>a (mm)</th>
<th>( \rho f ) (kg/m(^3))</th>
<th>( v^2 \times 10^{-5} ) (m(^3)/s)</th>
<th>( U ) (m/s)</th>
<th>Re</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>2.66</td>
<td>1.197</td>
<td>1.529</td>
<td>0.261</td>
<td>45.41</td>
<td>F,D</td>
</tr>
<tr>
<td>P2</td>
<td>3.75</td>
<td>1.197</td>
<td>1.529</td>
<td>0.278</td>
<td>68.18</td>
<td>F,D</td>
</tr>
<tr>
<td>P3</td>
<td>1.93</td>
<td>1.197</td>
<td>1.529</td>
<td>0.221</td>
<td>27.90</td>
<td>F,D</td>
</tr>
<tr>
<td>P4</td>
<td>3.22</td>
<td>1.197</td>
<td>1.529</td>
<td>0.271</td>
<td>57.07</td>
<td>F,D</td>
</tr>
<tr>
<td>P5</td>
<td>8.38</td>
<td>1.197</td>
<td>1.529</td>
<td>1.427</td>
<td>782.10</td>
<td>C,A</td>
</tr>
<tr>
<td>P6</td>
<td>2.62</td>
<td>1.197</td>
<td>1.529</td>
<td>1.241</td>
<td>212.65</td>
<td>C,A</td>
</tr>
<tr>
<td>P7</td>
<td>2.26</td>
<td>1.197</td>
<td>1.529</td>
<td>0.456</td>
<td>67.40</td>
<td>C,A</td>
</tr>
<tr>
<td>P8</td>
<td>2.78</td>
<td>1.197</td>
<td>1.529</td>
<td>0.490</td>
<td>89.09</td>
<td>C,A</td>
</tr>
</tbody>
</table>

\( Atm. \text{ Temp} = 22.0^\circ C, \text{ RH} = 42%, b = 1.04mm \)

\( T = \text{Tumbling}, F = \text{Fluttering}, C = \text{Stable Chaotic}, D = \text{Descending}, A = \text{Accenting} \)
3.9 Conclusion

This chapter has extensively explored the fundamental properties of ash created from a number of plant and tree species, with particular focus given to two of Australia’s most populated genera, the eucalypt and acacia. Investigations into the origins of ash demonstrated an inability to statistically correlate the properties of an ash particle to flame temperature. This was due to the high variability in the types of ash particles produced on small open fire tests. Here, some regions of fires were found to be cooler than others, resulting in ash particles that remained relatively intact and with large carbon content. In hotter regions, ash particles reached a maximum temperature and underwent complete combustion.

Considering alternative methods for creating ash, a linear burn chamber was proposed and was shown to create statistically correct particles based on image processing of open fire tests. Geometric information for the eight different genera was successfully extracted. This included measured probability distribution functions for projected area, aspect ratio and through thickness. Finally, shape classes were identified for ash. Larger scale ash was primarily found to be planar or cylindrical. On a small scale, spheroidal-shaped particles were
introduced to the classification. Distinguishing ash particles in this manner resulted in the notation of many similarities. Aspect ratio PDF’s were found to be identical between the eucalypt and wattle species, while a slight spreading of the projected area PDF’s was also noted. This spreading was theorised to be the result of the larger surface area present in the eucalypt species. Similarities were also found in the normalised mass loss and elemental composition, demonstrating identical behaviours to 400 °C. The normalised mass loss was identical in four different species.

The dynamic behaviour of the two large shape classes was shown to display three different dynamic modes. The eucalypt ash demonstrated all three modes, including the random chaotic mode in the ascent phase and the fluttering and tumbling modes in the descent phase. Conversely, pine was found to be predominantly influenced by its longitudinal stability. Whilst also demonstrating a random chaotic mode in the ascent phase, these ash particles only displayed the fluttering mode in the descent phase.

Particles in the ascent phase were shown to be affected by typical roll vortices generated by the thermodynamic cycles present in fires. These are typically described as horizontal or vertical roll vortices, which are inducements of large eddy swirls. Particles trapped inside these swirls will characteristically display trajectories similar to that of the moving air.

The development of statistical PDFs for the different types of ash as well as the analysis of their different dynamic properties provides answered to the first research question. The analysis undertaken provides a link between the geometries of smaller ash and smoke particles. These show typically spheroidal shaped geometry while larger ash particle which will proved significantly more scatter have geometries which are renitent of these original biomass. The large contrast in between planar and cylindrical shaped particles will become important when analysis the contributions of co and cross polarised electromagnetic waves in chapter 5.

The next requirement for analysing the scattering ability of ash particles is to investigate their fundamental RF material properties. This centres on understanding how effective relative complex permittivity and permeability values change with respect to temperature and moisture content.
4.1 Introduction

One of the primary objectives arising from the literature is to define how the relative complex permittivity of ash trends with respect to temperature. Furthermore, it is currently unknown if there are differences in the relative complex permittivity of various species or whether biomass as a material trends irrespective of the plant or trees being consumed in a fire. This chapter aims to extensively explore the relative complex permittivity of ash from a variety of plant and tree species, again focusing on the eucalypt and acacia genera.

The scattering of any medium can be described partly by analysing its relative complex permittivity and permeability. Both of these parameters are well established in Maxwell’s equations which are illustrated in Appendix A. Both the permittivity and permeability are defined as macroscopic material properties that affect the propagation path of an electric or magnetic field. The extraction of the relative complex permittivity and permeability at microwave frequencies can be carried out using a number of different methods. These include reflection only, transmission only, transmission/reflection methods and resonant methods as described in [139, 140]. All four methods have a number of advantages and disadvantages based on the type of material being analysed and the required accuracy. To measure the relative complex permittivity and permeability of ash, a number of considerations must be made. Firstly, the way in which the material is physically mounted within a sample holder must be addressed. From the analysis carried out within the previous chapters, the fragility of ash places a number of physical limitations on how and what can be measured about their material properties. This is mostly applicable to ash forming at high temperatures (>450°C). The second consideration relates to the magnetic component of ash. There are no ferrous materials present in ash, therefore in all cases this should be unity (i.e. \( \mu_r = \mu_0 = 1 + 0j \)).
Examining similar materials such as ash derived from black/brown coal or silica ash from volcanos, the permeability is unity and is unlikely to differ for all types of biomass [141-146]. To measure the complex forms of the permittivity and permeability, the transmission/reflection (T/R) method is most suitable. Here, the extraction of the transmission and reflection coefficient within a Material-Under-Test (MUT) can be achieved by calibrating, measuring and finally de-embedding S-Parameters taken using a Vector-Network-Analyser (VNA). Typically the T/R method is carried out within a transmission line. This is typically achieved using a coaxial or waveguide line section. Both these T/R transmission line measurements are described by Nicholson-Ross (NR) for transmission lines displaying TEM mode propagation, and Nicholson-Ross-Weir (NRW) for transmission lines displaying TE$_{10}$ modes [147, 148]. To measure the RF material properties of ash, the T/R waveguide method was chosen. This limits the need to obtain extremely accurate donut-shaped samples from the fragile biomass, which are then required to be accurately positioned inside the coaxial structure. The main limitation of the waveguide method is its limited bandwidth. An illustration of typical samples required for both the coaxial and waveguide transmission lines are illustrated in Fig. 77. In the case where the permeability is known to be unity, this can be used to judge the accuracy of the measurement.

Figure 75 – Typical sample holding arrangements for a) coaxial and b) waveguide T/R measurement for the extraction of S-parameters for determining a MUT’s relative complex permittivity and permeability. Coaxial samples are approximately 7mm in outer diameter while waveguide samples must fill the respective waveguide short and board wall dimensions.

Using the NRW T/R method, the permittivity ($\varepsilon$) and permeability ($\mu$) can be separated into their real and imaginary components defined by Eqn. (9) and Eqn. (10) [148].

$$\varepsilon = \varepsilon_r \varepsilon_0 = (\varepsilon'_r - j\varepsilon''_r)\varepsilon_0$$

(9)
\[ \mu = \mu_r \mu_0 = (\mu_r' - j \mu_r) \]  

(10)

Taking the measured changes in the transmission \( (S_{21}) \) and reflected \( (S_{11}) \) S-parameters from a MUT, the reflection coefficient can be defined by Eqn. (11).

\[ \Gamma = x \pm \sqrt{x^2 - 1} \]  

(11)

where,

\[ x = \frac{S_{11} - S_{21} + \Gamma}{1 - (S_{11} + S_{21})\Gamma} \]  

(12)

The propagation factor is given by Eqn. (13).

\[ P = \frac{S_{11} - S_{21} + \Gamma}{1 - (S_{11} + S_{21})\Gamma} \]  

(13)

Finally, the permittivity and permeability can be calculated by Eqn. (14) and Eqn. (15), respectively.

\[ \mu_r = \frac{1 + \Gamma}{\Lambda(1-\Gamma)} \sqrt{\frac{\varepsilon_r}{\mu_r}} \]  

(14)

\[ \varepsilon_r = \frac{\lambda_0^2}{\mu_r} \left[ \frac{1}{\lambda_c^2} - \left( \frac{1}{2\pi L} \ln \left( \frac{1}{P} \right) \right)^2 \right] \]  

(15)

where, \( L = \) Sample Length

\( \lambda_c = \) Waveguide cut-off Frequency

\( \lambda_0 = \) Measurement Frequency

and,

\[ \frac{1}{\lambda^2} = - \left( \frac{1}{2\pi L} \ln \left( \frac{1}{P} \right) \right)^2 \]  

(16)

*Note:* due to the complex nature of the propagation factor, the number of roots for a complex natural log is infinite (i.e. \( j + 2\pi n \)). Therefore, a branching index \( (n) \) needs to be defined in order to correct the function. See [139, 147, 148] for further details.
The electrical loss tangent can then be calculated by Eqn. (17).

\[
\tan \delta = \frac{\varepsilon''}{\varepsilon'}
\]

(17)

Where \( \varepsilon' \) = magnitude of real component

\( \varepsilon'' \) = magnitude of imaginary component

This chapter will proceed to investigate the RF material properties of fire-generated ash. The relative complex permittivity of ash will be investigated in two primary temperature regions. These include effective exposed temperatures below 400°C and effective exposed temperatures above 400°C.

### 4.2 VNA TRL Calibration

The waveguide transmission/reflection method used to determine the relative complex permittivity and permeability of materials is well suited for measuring ash. Prior to doing so, the VNA must be calibrated to level S-Parameter magnitudes and de-embed phases. The forward error model required to accurately calibrate a VNA is illustrated in Fig. 78. The figure illustrates the overall process required to carry out an 8-term THUE, LINE, REFLECT (TRL) calibration (see Fig. 79). The THUE measurement represents a straight transmission measurement between the waveguides. A length of LINE is then inserted, which is exactly a guided quarter wavelength at the mid-band frequency of the waveguide.

![Fig. 76 – VNA 8-term forward error calibration model used in a TRL calibration](image-url)
Chapter 4 – RF Properties of Fire Ash Particles

Calibration Steps

THRU

LINE

REFLECT

Setup Overview

VNA Setup

Sample and Holder

Fig. 77 – Waveguide LRL/TRL calibration setup and 5mm sample holder overview.
This is sufficient for the NRW waveguide method due to its limited bandwidth however in the case of a coaxial TRL calibration where a large calibrated bandwidth is required a dual band calibration is required.

Finally, the waveguide is shorted and the REFLECT measurement is taken. Once the calibration is completed, a sample can be measured by placing it in the holder as illustrated in Fig. 79. Only S_{11} and S_{21} are required to determine the relative complex permittivity of a material under test (MUT). Alternatively, S_{22} and S_{12} can also be taken and used in the NRW method to check for inhomogeneities within a material. A flow chart of the measurement procedure is illustrated in Fig. 80 and highlights some of the major steps required to reduce the error introduced by line insertion and reflections in the system. The calibration process is by far the most critical step in recording accurate measurements on a VNA. A total of five hundred and one data points over the frequency band were taken, giving a step size of approximately 4MHz.

![Flow chart](image)

*Fig. 78 – Flow chart demonstrating the measurement procedure used to measure samples using the NRW method. Most samples were tested more than three times over a number of different days to confirm repeatability of measurements.*
To show the accuracy of the extracted relative complex permittivity using the NRW method, dielectric measurements for a known standard (in this case Rogers Duroid 5880 substrate) have been presented in Fig. 81. The relative permeability ($\mu_r$) is displayed to show that the magnetic component is unity (i.e. $\mu_{\text{real}} = 1.00$ and $\mu_{\text{imag}} = 0.00$). The mid-band relative complex permittivity was extracted to be $\varepsilon_r = 2.24$. The approximate error in the extracted permittivity determined over numerous samples was determined to be $\varepsilon_r \pm 0.025$. The extracted permittivity is in accordance with the Rogers Duroid 5880 datasheet (www.rogerscorp.com).

![Graph showing relative permeability and permittivity.](image)

*Fig. 79 – Real (solid line) and imaginary components (dashed line) of the complex permeability and permittivity of a 0.125” Rogers Duroid 5880 substrate. Substrate measurement was used as a standard for determining measurement setup error.*

### 4.2.1 Unified Mixing Law

There are a number of methods for creating a mixing law from a material. These can include fitting a polynomial to measurements, altering existing mixing laws, or creating a new empirical formula for a material based on known constituents [149-152]. This dissertation has taken the approach of modifying Sihvola’s unified mixing law [153-156] to describe an empirical model for the powdered ash samples. The law can be corrected for
neighbouring scatter and polarisation effects by altering a dimensionless parameter \(v\) for a two-phase system (host phase and mixing phase). This modification allows the unified mixing law to describe a wide range of mixing models for different particle types. Sihvola’s unified law also presents a simple way to compare well-defined mixing laws to measured results.

As the small particulates of the samples (being the mixing phase) were found to be largely porous, a number of steps are now required to back calculate their effective complex relative permittivity. The inability to compress the powdered ash into a true homogeneous solid mass \(\varepsilon_i\) results in the creation of a mixed sample. To account for numerous complex dielectric variations in samples (due to the possibility of infinite volume fractions), an empirically matched mixing law is required. One of the main parameters for the differences found in mixing laws to those measured is the effects of neighbouring particulate scatter [157]. This is a direct result of the physical characteristics of the MUTs such as particle shape (i.e. geometry, aspect ratio etc), size distribution, density and orientation.

Work by Sihvola [153-156] has presented a unified mixing law theory (see Eqn. (18) and Eqn. (19)). The introduction of a dimensionless parameter \(v\) allows for depolarisation variations to be corrected for a two-phase system. Theoretically, there is no limit for the depolarisation factor as \(v\) is highly influenced by particle geometry [154, 157] and not the isotropic properties of a material. The unified mixing law can be used to describe a number of popular mixing laws simply by changing the depolarization factor \(v\). Examples of this include the case where \(v = 1\) (Maxwell-Garnett), \(v = 2\) (Bruggeman) and \(v = 3\) (Coherent Potential).

\[
\frac{\varepsilon_{\text{eff}} - \varepsilon_e}{\varepsilon_{\text{eff}} + 2\varepsilon_e + v(\varepsilon_{\text{eff}} - \varepsilon_e)} = f_v \frac{\varepsilon_i - \varepsilon_e}{\varepsilon_i + 2\varepsilon_e + v(\varepsilon_{\text{eff}} - \varepsilon_e)}
\]

(18)

\[
\varepsilon = \varepsilon_r \varepsilon_0 = (\varepsilon'_r - j \varepsilon''_r) \varepsilon_0
\]

(19)

where, \(\varepsilon_e\) = Complex relative permittivity host phase (air)
\(\varepsilon_i\) = Complex relative permittivity of mixing phase (solid ash)
\(\varepsilon_{\text{eff}}\) = Effective complex relative permittivity of mixing phase (measured)
\(f_v\) = Volume fraction (solid/environment)
\(v\) = Dimensionless parameter
Chapter 4 – RF Properties of Fire Ash Particles

Rearranging and solving the unified mixing law for $\varepsilon_{\text{eff}}$ the resultant equation is derived (see Eqn( 20 )).

$$
\varepsilon_{\text{eff}} = - \frac{(2\varepsilon_e + \varepsilon_i + \varepsilon_f v - \varepsilon_i f_v - 2\varepsilon_e v - A + \varepsilon_f f_v v - \varepsilon_i f_v v)}{(2v)}
$$

(20)

Where,

$$
A = \sqrt{B + C + D}
$$

$$
B = \varepsilon_e^2 f_v (f_v v^2 + 2f_v v + f_v - 8v + 4 + \frac{4}{f_v})
$$

$$
C = \varepsilon_e \varepsilon_i f_v (-2f_v v^2 - 4f_v v - 2f_v + 10v - 2 + \frac{4}{f_v})
$$

$$
D = \varepsilon_i^2 (f_v^2 v^2 + 2f_v^2 v + f_v^2 - 2f_v v - 2f_v + 1)
$$

The complexities of the particulate geometry within the powdered ash were illustrated in section 3.6.4.2. Similarities between the particles over all six genera were also shown. The random nature of the mixing phase (i.e. the ash) will create complex scattering. The complex 3-dimentional structures of the particles will directly impact upon the depolarization factor ‘v’ [153, 154, 157].

At this present stage, two unknown parameters of the ash samples must be determined. These parameters are a complete relative complex permittivity model for the ash samples with respect to volume fraction (solid material/environment inclusion (air) ratio), and the equivalent effective solid relative permittivity ($\varepsilon_{\text{i,real}}$) and loss tangent ($\tan(\delta) \sim \varepsilon_{\text{i,imag}}/\varepsilon_{\text{i,real}}$). It should be noted that the effective solid relative permittivity and loss tangent are hypothetical points for fire ash, however; they are required to describe the mixing law for the complete range of volume fractions (i.e. 0% to 100%). The models are expected to predict the complex dielectric property of flying forest ash. This is a result of the collated ash particles being extremely fragile, leading to a powdered ash measurement process. As the ash particles are highly porous (due to their organic cell structures), a mixing law is required to back calculate the effective dielectric property of an equivalent homogeneous material.
Applying any mixing law does not however, guarantee an accurate description of a material’s properties [152]. This is the case when the inclusion material (the mixing phase) has larger geometric particle differences to those assumed in mixing laws such as [153, 154]. Moisture content and sample temperature also play an important role in determining the relative complex permittivity as will be shown in the subsequent sections of this chapter.

**4.3 Effective Relative complex permittivity of Ash Created in Uncontrolled Fires Conditions**

As has been demonstrated, high temperature ash poses a number of challenges due to its fragility. Most of these challenges arise when the biomass is exposed to temperature ranges greater than 400 °C. To circumvent this problem, the dielectric measurements of powdered ash can also be investigated using the Nicholson-Ross-Weir method. Relating to other remote sensing fields can assist in better understanding these uncontrolled samples. In recent years there have been a number of studies carried out to determine the dielectric properties of different volcanic ash samples in order to understand how pyroclastic cloud particles interact with microwave signals [141, 144, 145]. This research provides a primary background in radar system performance in volcanic remote sensing and atmospheric modelling.

The knowledge gained about what effect the exposed temperature has on the relative complex permittivity is only relevant under even heating conditions. This analysis is important and will be discussed further in section 4.4 and 0. It is also useful to analyse the effective relative complex permittivity of ash created from within fires of known peak flame temperature. This information provides a window into the expected variations in the scattering anticipated for different biomass under similar burning conditions. This further demonstrates the independency of a fire’s peak flame temperature and the effective exposed temperature of ash as hypothesised in Chapter 3.

It has been shown that there is a large variation in the amount of stored energy within different plant and tree species available to be released to fuel fires [158-162]. This also changes based on the time of year due to seasonal temperatures and average rainfall which directly effects the degree of curing (DoC) of the biomass [159].

Ashes created from the six different genera explored within this dissertation have been measured for their effective relative complex permittivity in these uncontrolled fire conditions. All samples were naturally burnt, reaching peak flame temperatures between 800-
900 °C. The eucalypt sample was burnt at a much higher peak flame temperature (*between 1000-1100 °C*), to limit the amount of carbonaceous material remaining within the material. This was achieved with the aid of the high temperature propane flame built into the chamber. The burnt ash particles of cross-sectional lengths ranging between 1 mm to 5 mm were then taken and ground to a fine powder. The final step included passing the powder through a number of fine meshes (0.25 mm x 0.25 mm) to remove larger solids.

The material properties of the test specimens are described in Table 11, while examples of the ground ash used for the relative complex permittivity measurements are illustrated in Fig. 80. The table provides all the determined physical parameters for the ash including the bulk density and specific/solid density values along with the equivalent volume fraction (*f_v*). For the purpose of the measured results, it is assumed that the moisture content in all ash samples is negligible. Efforts were made to prevent moisture absorption by resting the ash on a hotplate at low temperatures. (*It should be noted that a small percentage of water will always remain within the ash samples, as demonstrated by the absorption plots illustrated in Fig. 61*). Samples were again collected from ground litter, however; here they were left to dry for four weeks. The exception to this was the pine sample, which was collected and processed on the same day. Here, the air velocity and fuel loading factor were changed to reach the desired peak flame temperatures of 800 °C -900 °C and 1000 °C -1100 °C.

<table>
<thead>
<tr>
<th>Sample</th>
<th>TEMP. RANGE (°C)</th>
<th>Specific Gravity (g/cc)</th>
<th>Bulk Density (g/cc)</th>
<th><em>f_v</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt</td>
<td>1000-1100</td>
<td>2.84</td>
<td>0.87</td>
<td>0.306</td>
</tr>
<tr>
<td>Eucalypt - Wet**</td>
<td>1000-1100</td>
<td>2.84</td>
<td>1.11</td>
<td>0.391</td>
</tr>
<tr>
<td>Wattle</td>
<td>800-900</td>
<td>2.01</td>
<td>0.60</td>
<td>0.300</td>
</tr>
<tr>
<td>Bracken Fern</td>
<td>800-900</td>
<td>1.95</td>
<td>0.69</td>
<td>0.305</td>
</tr>
<tr>
<td>Sheoak</td>
<td>800-900</td>
<td>2.95</td>
<td>0.89</td>
<td>0.301</td>
</tr>
<tr>
<td>Radiata Pine</td>
<td>800-900</td>
<td>2.11</td>
<td>0.63</td>
<td>0.289</td>
</tr>
<tr>
<td>Cypress</td>
<td>800-900</td>
<td>2.35</td>
<td>0.71</td>
<td>0.301</td>
</tr>
</tbody>
</table>

*The volume of the sample holder remained constant at 1.161 cm³*

**This is based on the dry mass content within the holder. The volume fraction for water within sample is *f_v*water = 0.467
To provide some analysis of the response of the ash created from the different genera, a snapshot of the relative complex permittivity at approximately 30% volume fraction will be presented. This snapshot will be expanded to look at the response of the ash over different volume fractions thus allowing the equivalent solid permittivity to be approximated using the unified mixing law. The data provided in Table 11 is sufficient for solving this mixing law. The volume fraction for the sample can be calculated from Eqn. (5). Furthermore, the frequency response of the ash will also be investigated. For a weakly dispersive material it can be shown that the frequency response over typical waveguide bandwidths can be assumed to be linear.
Fig. 80 – Ash samples used in dielectric constant measurement in order of light to darks, a) Eucalypt, b) Cypress, c) Bracken Fern, d) Sheoak, e) Wattle.
The Eucalypt sample was tested under two conditions: dry, and with 30% moisture content by weight (w/w). Both relative complex permittivity measurements are illustrated in Fig. 81.

![Graph showing real and imaginary components of complex permeability and permittivity](image)

Fig. 81 – Real (solid line) and imaginary components (dashed line) of the complex permeability and permittivity of a dry and wet eucalypt sample. Wet real and imaginary components are represented by the upper solid and dashed line while the dry real and imaginary components are represented by the lower solid and dashed lines. Samples measured at 22.8°C with water concentration of 30% w/w

The high dielectric of the sample containing moisture is a direct result of the high relative complex permittivity of water ($\varepsilon_r \approx 62$ at 10GHz). The imaginary part of the permittivity indicates that the material is extremely lossy which is caused again by the inclusion of water. Furthermore, the dielectric properties have become slightly frequency dependent, also a result of the inclusion of water. With the removal of a majority of the carbonaceous content within the dry eucalypt ash, a good representation of the base material’s relative complex permittivity can be seen. The most noticeable effect of burning the eucalypt at these higher temperatures is the lack of carbonaceous material remaining in the powdered ash. As demonstrated by its relative complex permittivity, the imaginary component is extremely low. Carbon, in its many forms, is known to be an extremely lossy material. This is partly due to its weak AC and DC conductivity components which on the atomic level is caused by its ability to form into different crystalline structures with various bonding arrangements.
With consideration to other plant species burnt in low temperature fires, the opposite outcome is evident in the imaginary component. This is illustrated for wattle, bracken fern, sheoak, pine and cypress in Fig. 83, Fig. 84, Fig. 82, Fig. 85 and Fig. 86 respectively. Here, their loss tangents are shown to be significantly high due to the remaining carbonaceous compounds (represented by the darker colour of the ash illustrated in Fig. 80).

Moreover, the real components also follow a generalised trend in this direction. As the material becomes more conductive due to the inclusion of carbon a generalised increase can be seen. A summary of the dielectric constant and loss tangent for the biomass samples demonstrated with similar volume fractions is presented in Table 12.

![Dielectric properties graph](image)

*Fig. 82 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a Wattle Tree sample at 22.8°C.*
Fig. 83 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a 
bracken fern sample at 22.8°C.

Fig. 84 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a sheoak sample at 22.8°C.
Fig. 85 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a Radiata Pine sample at 22.8°C.

Fig. 86 – Real (solid line) and imaginary parts (dashed line) of the dielectric constants measured from a Cypress Tree sample at 22.8°C.
**Table 12: Summary of results at mid-band frequency (10 GHz)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Dielectric ($\varepsilon$)</th>
<th>Loss Tangent ($\delta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt (dry)</td>
<td>2.32 ± 0.025</td>
<td>0.005 ± 0.0025</td>
</tr>
<tr>
<td>Eucalypt (wet)</td>
<td>21.20 ± 0.025</td>
<td>0.610 ± 0.0025</td>
</tr>
<tr>
<td>Bracken Fern</td>
<td>1.95 ± 0.025</td>
<td>0.063 ± 0.0025</td>
</tr>
<tr>
<td>Sheoak</td>
<td>3.45 ± 0.025</td>
<td>0.126 ± 0.0025</td>
</tr>
<tr>
<td>Wattle Tree</td>
<td>3.13 ± 0.025</td>
<td>0.128 ± 0.0025</td>
</tr>
<tr>
<td>Radiata Pine</td>
<td>4.48 ± 0.025</td>
<td>0.186 ± 0.0025</td>
</tr>
<tr>
<td>Cypress</td>
<td>2.85 ± 0.025</td>
<td>0.058 ± 0.0025</td>
</tr>
</tbody>
</table>

It is clearly illustrated in Table 12 that the dielectric constant varies with species of flora based on their natural burning conditions. This is further supported by the known differences in the amount of energy stored within different plant and tree species [158-164]. The permittivity has been shown in all cases to be relatively linear over the X-Band frequency range. As the ash has this linear response the mid-band frequency will give a reasonable representation of the relative complex permittivity of the ash. Expanding on this single volume fraction point the ash can be now measured and characterised over different volume fractions for build a mixing law model.

### 4.3.1 Fitted Dielectric Mixing Law Models for Uncontrolled Samples

This section presents an empirical mixing law for the uncontrolled ash samples over X-Band (8-12 GHz). Due to the linear response of the ash over this band only data for the mid-band frequency of 10 GHz will be displayed. Again the NRW transmission/reflection method has been employed, with the analysis now taking into consideration different volume fractions [147, 148]. A minimum number of ten different volume fractions for each of the six species were measured over X-Band. The complex relative permittivity of each sample was measured at volume fractions ranging from approximately 0.15 to 0.45. Below this fraction range, the samples could not physically be held inside the sample holder. Similarly at fractions above this, the ash could not be compacted any tighter.

The samples were prepared and stored under a partial vacuum to reduce moisture absorption during storage time. Measurements were carried out at a room temperature of 22.8 °C and with an average relative humidity of 51.5%.

Applying Sihvola’s unified mixing law to the measured results, two parameters were optimised to find an empirical model for each of the samples. These included the
dimensionless parameter ‘v’ and solid/inclusion relative complex permittivity ‘ε_i’. The optimisation process was carried out by firstly altering ‘v’ to find the relative solid permittivity ‘ε_i’ for the measured data points. If the mixing law has perfect agreement, ‘ε_i’ should be identical for every measurement point for any volume fraction. The average of all ‘ε_i’ values was then used to re-solve the mixing law. The error between the average ‘ε_i’ and mixing law at each measured point was minimised. The process was then repeated until an optimised result was reached. The complex forms of the permittivity were used to solve the mixing formulation. This trial-and-error based approach at optimisation was successful in find the best agreement for the complex form of the permittivity.

The results of the optimised mixing law models for each of the species are illustrated in Fig. 87, Fig. 88, Fig. 89, Fig. 90, Fig. 91 and Fig. 92. A comparison between the Maxwell-Garnett (v = 1), Coherent Potential formula (v = 3) and a large depolarisation factor (v = 20) has also been included to demonstrate what effects the depolarisation factor has on mixing law results. The corresponding optimised dimensionless parameters (v) used within the unified mixing law formula are presented in Table 13. The matching of the mixing law is again shown to be in accordance with the measured results, whilst the depolarisation factor for all plant species is again found to be almost identical for all types of ash. The ash when compared to the traditional mixing law models such as Maxwell-Garnett (v = 1), Bruggeman (v = 2) and Coherent Potential formula (v = 3), shows a much more linear response over a majority of the higher volume fractions. This is unlike the traditional models, which are more non-linear with respect to volume fraction. Both the real and imaginary components show excellent agreement.

The validity of the mixing law is bound by how well the volume fraction of the powdered ash is known. As described in section 3.7.4 where the solid density was extracted from the ash, some difficulties were encountered due to ash having a highly complex internal closed cell structure. These structures, especially in the case where large amounts of carbonaceous material remains inside the ash, result in some remaining porosity and subsequently a lower than expected solid density value. The effects of this lower solid density value must be analysed with respect to the unified mixing law. As shown by the mixing law illustrations, a predominant outcome in the results is the shifting of each point left or right along the volume fraction axis. The effective relative complex permittivity values will not change respectively to each other, thus the depolarisation factor will be identical. In this case, the main effect of a lower solid density value centres on the inclusion/solid relative complex permittivity of the
ash. As the solid density value decreases, the result is an increase in the volume fraction. As the volume fraction increases, the inclusion relative complex permittivity will decrease.

---

**Fig. 87** – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for dry eucalypt ash. Optimal when \( v = 10.10 \)

**Fig. 88** – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for dry wattle tree ash. Optimal when \( v = 10.60 \)
Chapter 4 – RF Properties of Fire Ash Particles

Fig. 89 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for dry bracken fern ash. Optimal when $v = 10.06$

Fig. 90 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for dry sheoak ash. Optimal when $v = 9.95$
Chapter 4 – RF Properties of Fire Ash Particles

Fig. 91 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for un-dried pine ash. Optimal when $v = 10.40$

Fig. 92 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for dry cypress ash. Optimal when $v = 9.99$
Chapter 4 – RF Properties of Fire Ash Particles

Table 13: Summary of mixing law results at mid-band frequency (10 GHz)

<table>
<thead>
<tr>
<th>Sample</th>
<th>( v )</th>
<th>( \varepsilon_{\text{real}} )</th>
<th>( \varepsilon_{\text{imag}} )</th>
<th>( \tan(\delta) )</th>
<th>( \rho ) (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt</td>
<td>10.10</td>
<td>6.30</td>
<td>0.06</td>
<td>0.0095</td>
<td>2.84</td>
</tr>
<tr>
<td>Bracken Fern</td>
<td>10.06</td>
<td>4.85</td>
<td>0.51</td>
<td>0.1052</td>
<td>1.95</td>
</tr>
<tr>
<td>Sheoak</td>
<td>9.95</td>
<td>10.05</td>
<td>1.76</td>
<td>0.1751</td>
<td>2.95</td>
</tr>
<tr>
<td>Wattle Tree</td>
<td>10.60</td>
<td>11.44</td>
<td>1.71</td>
<td>0.1495</td>
<td>2.01</td>
</tr>
<tr>
<td>Cypress</td>
<td>9.99</td>
<td>8.68</td>
<td>0.85</td>
<td>0.0979</td>
<td>2.35</td>
</tr>
<tr>
<td>Pine</td>
<td>10.40</td>
<td>16.99</td>
<td>3.51</td>
<td>0.1854</td>
<td>2.11</td>
</tr>
</tbody>
</table>

Table 14: Summary of fitting errors for measurements and mixing model

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \varepsilon_{\text{eff}} )</th>
<th>Max. §</th>
<th>Ave. **</th>
<th>Max. +</th>
<th>( \varepsilon_{\text{imag}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt</td>
<td>±0.025</td>
<td>1.47%</td>
<td>0.73%</td>
<td>2.37%</td>
<td></td>
</tr>
<tr>
<td>Bracken Fern</td>
<td>±0.025</td>
<td>3.68%</td>
<td>1.61%</td>
<td>6.85%</td>
<td></td>
</tr>
<tr>
<td>Sheoak</td>
<td>±0.025</td>
<td>4.17%</td>
<td>2.07%</td>
<td>6.78%</td>
<td></td>
</tr>
<tr>
<td>Wattle Tree</td>
<td>±0.025</td>
<td>3.63%</td>
<td>1.70%</td>
<td>7.14%</td>
<td></td>
</tr>
<tr>
<td>Cypress</td>
<td>±0.025</td>
<td>4.40%</td>
<td>2.78%</td>
<td>6.81%</td>
<td></td>
</tr>
<tr>
<td>Pine</td>
<td>±0.025</td>
<td>5.82%</td>
<td>2.63%</td>
<td>7.98%</td>
<td></td>
</tr>
</tbody>
</table>

* Dielectric measurement error from Vector Network Analyser
§ Maximum percentage error between empirical curve and measured points
** Overall average percentage error between empirical curve and measured points
+ Maximum percentage error between \( \varepsilon_{i} \) determined from each data point for optimal solution

Considering the geometry of the ash explored in section 3.6.4, the species sampled within this dissertation are shown to be far from spheroidal in shape. This is further complicated by three-dimensional cellular sub-structures present within plants. The correction to the dimensionless parameter for the depolarisation effects is significant, shown in the high value for ‘\( v \)’. This result may be attributed to the types of geometric variations in the ash particles.

The cell structures of the different plant and tree species have been shown to be very similar. The resultant depolarisation factor maybe successfully implemented in the unified mixing law for describing the relative complex permittivity of a diverse range of different plant and tree species. Ash geometry can be considered to be a mixture of planar (sharp edged) or spheroidal with capillary cavities. The effect of these cavities may contribute to the depolarisation effects experienced by the electric field passing through the medium. The contributions of the remanent cell structures to the depolarisation factor will need to be studied in further detail to assess what causes a higher outcome. The effects of this higher depolarisation factor will also play a role in describing the complex relative permittivity of ash particles suspended within the atmosphere. In reality, as an electric field passes through an ash particle, it will experience similar macroscopic displacements. The scattering
attributed to ash particles will show similar effects, however; as the particles increase in size, changes to the depolarisation factor are yet undetermined.

The measurements of the six ash samples also highlight the flexibility of the unified mixing law. The effective relative complex permittivity of the ash can then be easily extracted once each of the parameters are known. This provides a more robust method of modelling the permittivity than traditional polynomial fitting methods. This is especially true when the effects of moisture absorption on relative complex permittivity are required to be added to the mixing phase.

The percentage error between the optimised mixing law and the measured data points shown in Table 14 and is within a respectable limit. The fitting errors are similar to those predicted by Hallikainen [165] for soil relative complex permittivity measurements using a similar back optimisation approach.

4.3.2 Effects of Particle Geometry on the Unified Mixing Law

The effects of particle geometry on the unified mixing law will be explored within this section. This analysis is required as there is little known practical implementation of the unified mixing law beyond low depolarisation factors. As ash has a complex internal structure, it is important to fundamentally explore what is creating the significantly high depolarisation factor. This analysis is also important when considering the bulk refractive index of free-space containing large planar or needle-shaped ash particles. Shape trends have been established for mixing laws, however; shape and size classifications have rarely been identified for larger particles in literature [153, 154, 156]. To achieve an analysis of the unified mixing law, simulated waveguide data using particles of the same relative complex permittivity values have been carried out. The difference between each simulation is the geometric properties of the particles. Two geometric cases have been explored here; one that represents randomly sized spheres and a second, which includes randomly shaped rectangular plates with constant thickness. Both cases have implemented two further size classifications between a distributed diameter or length between 0.5-1.0 mm and 1.0-1.5 mm. The resultant mixing law models and their fitted depolarisation factor for randomly shapes spheres are illustrated in Fig. 93 and Fig. 94 respectively.
Fig. 93 – Simulated (‘S’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for random spheres 0.5-1.0mm diameter. \( \varepsilon_i = 10+0.2i \), resultant depolarization factor \( v=1.5 \).

Fig. 94 – Simulated (‘S’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for random spheres 1.0-1.5mm diameter. \( \varepsilon_i = 10+0.2i \), resultant depolarization factor \( v=2 \).
Chapter 4 – RF Properties of Fire Ash Particles

Fig. 95 – Simulated (‘S’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for random plates of thickness 0.1mm at 0.5-1.0mm (LxW). \( \varepsilon_i = 10+0.2i \), resultant depolarization factor \( v=75 \)

Fig. 96 – Simulated (‘S’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity for random plates of thickness 0.1mm at 1.0-1.5mm (LxW). \( \varepsilon_i = 10+0.2i \), resultant depolarization factor \( v=14 \)
As illustrated in Fig. 93 and Fig. 94, the spherical case shows the unified mixing law is in accordance with the traditional Maxwell-Garnett and Bruggeman mixing laws. The deviation in the depolarisation factor is not significant moving from $v = 1.5$ to $v = 2.0$ when the particle distribution increases. An interesting shift in the depolarisation factor is achieved when considering rectangular plates (see Fig. 95 and Fig. 96). Here, the depolarisation factor moves from $v=75$ to $v=14$ over the two size classifications. The large depolarisation factor inherently found within all the powdered ash samples measured can be explained by these complex shaped particles. It is known that on the macroscopic level (as shown in section 3.6.4) ash is typically made of spherical, planar and cylindrical shaped geometry. The average depolarisation factor ($v \sim 10$) of the ash indicates exactly these types of particulate geometries. As the depolarisation factor increases with smaller planar particle geometries, it is likely that an interacting electric field will see a medium that is slightly spherical/cylindrical in nature. This results in a reduction of the average depolarisation factor due to the lower depolarisation factors of these spherical/cylindrical particles. Overall however, the particles have a more planar geometry resulting in a larger depolarisation factor.

The importance of mixing laws in describing the behaviour of ash as a material can also be extended to examining the bulk relative complex permittivity of ash particles in free space. This particularly applies to the planar geometries of the eucalypt and acacia genera explored within this dissertation. As demonstrated in Fig. 95 and Fig. 96, planar geometries have a more linear increase with volume fraction compared to spheroidal geometries. Examining a case where the planar ash particles experience those dynamic modes explored in section 3.8 under the descent phase, the bulk permittivity of a volume will increase at a much more linear rate. This in effect will cause the reflectivity to be more linear, thus an approximate extraction of the concentration of ash particles within a unit volume can be obtained. This in turn supports the argument that radar systems observing fires will have a more linear relationship between reflectivity and particle concentrations, thus making it possible to estimate the amount of biomass consumed in a fire.
4.4 Relative Complex Permittivity of Controlled Ash at Low Temperatures (≤ 400 °C)

Extraction of the relative complex permittivity of controlled samples is an important step in realising a model that defines material changes with respect to temperature. As demonstrated throughout Chapter 3, the ash structure remains intact to 400 °C. Between 400 °C and approximately 450 °C, the ash begins to ember and loses a significant portion of its mass and cell structure, thus becoming too fragile to handle. To successfully extract the relative complex permittivity, there are certain sample requirements that must be fulfilled. Firstly, the MUT sample must be planar and mounted perpendicular to the propagating electric field. Furthermore, there cannot be any air gaps around the edges of the MUT. With consideration to the various types of biomass, the scope of samples suitable for such testing is then limited to large, broadleaf structures. The extraction of the relative complex permittivity for needles such as the foliage common to sheoak pine and cypress for example, will require a hybrid measurement where a back-optimisation approach will need to be implemented to determine the relative complex permittivity. Here, an electromagnetic simulation model is made to measure S-Parameter data.

The thickness of the broadleaf species (eucalypt and wattle) analysed within this dissertation have shown distributions peaking between 0.267 mm and 0.3036 mm. Thickness cross-sections using MicroCT analysis have demonstrated that the surface of the broadleaf species is rough. This rough texture increases with temperature as the cell structure begins to shrink (see Fig. 37). As the surface finish of the leaves cannot be altered in any way, the “roughness” will be an inherent error induced into the extraction method. To ensure that the leaf samples are covering the entire waveguide cross-section, a specially designed sample holder is required. This sample holder consists of three waveguide sections where leaf samples are held in place using a thin brass shim. The entire sample holder structure is illustrated in Fig. 97.

The brass shim is designed to have a slightly larger cross section than the waveguide being measured. The gap introduced here is approximately 0.25 mm. The thickness of the shim is ~0.3 mm to correspond to the approximate mean thickness of the samples. The three line sections are held together using two small countersunk taps that align the waveguides. The effects of the shim in the completed line (see Fig. 97. b)) are calibrated in the standard TRL calibration. The shim slightly alters the overall impedance of the waveguide by increasing the
inductance and decreasing the capacitance of the line. To minimise these effects, the gap has been minimised to ensure matching over the entire band to be tested. No noticeable filtering responses have been detected using this waveguide holder, and extraction of the relative complex permittivity from a 0.254 mm Rogers 5880 Duroid sample was achieved with excellent results.

Fig. 97 – Waveguide sample holder used to ensure ash samples are held perpendicular to a propagating electromagnetic field. a) exploded view of holder, b) assembles holder, c) 0.25mm gap in the length and width of the shim waveguide dimensions and d) placement of ash in the waveguide shim

4.4.1 Sample Preparation

Correct sample preparation is essential when analysing the relative complex permittivity of a material and for accurate results, samples must be as planar as possible. Samples from the specified eucalypt and acacia genera (*messmate, spotted gum, iron bark and blackwood wattle*) were collected from a variety of trees. The samples were randomly selected to include juvenile and adult leaves.

Upon collection the leaves were weighed, scanned and their average thickness measured. To assist in the drying and pressing process of the samples, the entire leaf collection was
Chapter 4 – RF Properties of Fire Ash Particles

pressed using 30 mm thick panels of MDF (Medium Density Fibreboard) wood. MDF is a type of engineered fibreboard that is notably heavy and will readily take in moisture, aiding in the drying process. Samples were left to dry upwards of two months with regular rotations (to avoid the leaves sticking to the MDF board). Weight, scans and average thickness measurements were also taken. Weight stabilisation was generally achieved within 4-6 weeks, however to ensure planar leaf structures, extra time was given.

The leaf structures were then exposed to designated temperature ranges mapped in Chapter 3 and for the given exposure times highlighted in Fig. 56. These included an unburnt sample and samples exposed from 150 °C to 400 °C at 50 °C intervals.

The heating process was carried out on one leaf at a time using a temperature controlled hot plate. A hotplate was found to provide better temperature stability compared to an oven due to the environment remaining effectively constant for the hotplate (i.e opening the oven door cools the heating cavity down) Samples were also lightly pressed using a thick metal plate. This aided in maintaining each samples planarity over the heating cycle.

Once the samples were prepared sections of the leaf were cut using the brass shim as a stencil. The sample holder was screwed together and the measurements carried out as per the measurement procedure outlined in Fig. 78. It should be noted that the samples are best suited for waveguide measurements in WR-90 and below, where the frequency is greater than 8GHz. The WR-90 waveguide has an internal broad wall dimension of 22.86 mm and a short wall dimension of 10.16 mm. The next largest waveguide is WR-137, which has an internal broad wall dimension of 34.85 mm and a short wall dimension of 15.80 mm. As demonstrated, the cross sectional area of the waveguide is compared to WR-90 rendering it less suitable for many types of broadleaf foliage. Examples of the sample preparation process for the messmate eucalypt leaves can be observed in Fig. 98. As demonstrated, the biomass begins to brown at the 200 °C mark before it darkens towards states of black carbon at 400°C. The structures at 400 °C are still intact with no flaming or ember regions, therefore samples are still suitable for measuring relative complex permittivity using the NRW method.
Fig. 98 – Examples of messmate eucalypt leaves collected, dried/pressed and exposed at various temperature ranges.
4.4.2 Relative Complex Permittivity at X-Band (8 – 12 GHz) and Ka-Band (26.5 – 40 GHz)

The extracted dielectric constant and loss tangent for three broadleaf structures (messmate eucalypt, iron bark eucalypt, spotted gum and blackwood wattle) have been carried out. Measurements have been covered primarily at X-band (8 – 12 GHz) with limited measurements a Ka-band due to similarities noted in the material properties. These will be discussed further within this section.

Many materials measured at microwave and millimetre wave frequencies typically display a polar response [139, 140, 166, 167]. For dielectric materials this response is weakly dispersive and can be modelled quite accurately over various wavelengths using a Debye type dispersion model [167]. This approach has successfully been implemented in characterising highly polar materials such as water [168-170] and snow [169]. As ash retains a large percentage of moisture by weight at natural saturation (up to 6% w/w, see section 3.7.3) it is expected the relative complex permittivity will display a weak dispersive response over a wide frequency range. In this scenario the real component of the permittivity will slowly decrease with frequency while the loss tangent will slowly rise. This polar effect of a material in the presence of an alternating field can be seen clearly in [170] for example.

Unlike the effective exposed temperature explored in ash, the ambient measurement temperature also has an effect on the relative complex permittivity of polar materials. For the case of fires where particles are reaching significantly high internal temperatures thermal effects should be considered. However, in a practical case where the particles are interacting with an electromagnetic field some distance above a fire the influence of temperature dependency can be neglected. The Results of the measured relative complex permittivity for the three eucalypt and the single wattle species at X-Band are illustrated in Fig. 99, Fig. 100, Fig. 101 and Fig. 102. The relative complex permittivity has been displayed here at 10 GHz only as the response is close to linear over the entire band.

Demonstrated by the measurements is the remarkable similarity between all species measured given the small population of samples. The permittivity of the eucalypt specimens are shown to be identical under all temperature conditions. The wattle is also very similar however its initial permittivity is slightly higher than the eucalypt. The loss tangents do show some variation however the extraction of the lost tangent is difficult for thin samples.
The similarities can be explained by looking at the elemental composition of the biomass discussed in section 3.7.2. Shown were the similarities in the way the primary elements changed in concentration with increase in the effective exposed temperature.

*Fig. 99 – Box-plot of dielectric constant and loss tangent for messmate eucalypt leaves exposed to various temperatures. X-Band mid-band response at 10GHz, Ambient Temp 22°C, RH 42%.*
Fig. 100 – Box-plot of dielectric constant and loss tangent for blackwood wattle leaves exposed to various temperatures. X-Band mid-band response at 10GHz, Ambient Temp 23°C, RH 49%.
Fig. 101 – Box-plot of dielectric constant and loss tangent for spotted gum leaves exposed to various temperatures, X-Band mid-band response at 10GHz, Ambient Temp 22°C, RH 34%.
Fig. 102 – Box-plot of dielectric constant and loss tangent for iron bark eucalypt leaves exposed to various temperatures, X-Band mid-band response at 10GHz, average ambient measure temp. 22°C, RH 35%.
From this analysis it is suggested that interacting electric fields are primarily seeing a lossy carbonised material. They are not showing any distinct deviations due to changes in the molecular chemical composition, which occur during the decomposition of the biomass. The plateau of the relative complex permittivity in all samples at 400°C is most likely the result of the larger saturation level, as illustrated in the absorption characterisation in Fig. 61. It is not likely to be present in a moisture deficient sample.

The question now arises as to what happens to the relative complex permittivity of the biomass samples at smaller wavelengths. Transitioning to smaller waveguides introduces a number of new complexities. These include poorer calibrations due to tolerances in mating flanges and the ability to cut samples accurately to fit inside small waveguide cross-sections. As the four species measured at X-Band show extremely similar behaviour, only the messmate eucalypt will be measured at Ka-Band. The WR-28 Ka-Band waveguide is 7.11mm in broad wall length and 3.55mm in short wall length. The analysis frequency of 38GHz has been extracted from the entire band to give a good indication of the total change in the material’s relative complex permittivity from 10GHz. The results of the Ka-Band measurements are illustrated in Fig. 103.

In comparison to the X-Band results, the permittivity shows no significant change. The major difference is the loss tangent, which is slightly higher at Ka-Band. These observable trends are characteristic of many dispersive dielectric materials. A model to best describe the wideband response of the material can be achieved using a first order Debye model given by Eqn. (21).

\[
\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau}
\]  

(21)

Where \(\varepsilon_r\) is the relative permittivity, \(\varepsilon_\infty\) is the optical permittivity, \(\varepsilon_s\) is the static (or DC) permittivity, \(\omega\) is the angular frequency \((2\pi f)\) and \(\tau\) is the relaxation time. For example, a fitting model for the unburnt biomass gives \(\varepsilon_\infty \sim 2.25\), \(\varepsilon_s \sim 2.37\) and \(\tau\) having the relaxation time of water \((\sim 8.27e-3\) ns) [167]. This will change at each effective temperature range due to the different permittivity values shown. Before an extended model can be created, the analysis of the relative complex permittivity at higher temperatures is required.
Fig. 103 – Box-plot of dielectric constant and loss tangent for messmate eucalypt leaves exposed to various temperatures, Ka-Band response at 38GHz, average ambient measure temp. 21°C, RH 35%.
4.5 Relative Complex Permittivity of Controlled Ash at High Temperatures (> 400 °C)

To gather a complete understanding of the relative complex permittivity of the genera, measurements at higher temperatures must be analysed. The relative complex permittivity of these higher temperature ash samples is difficult to measure due to the fragility of ash. To overcome this issue, ash can be turned into a powder where it is then representative of the originating ash structure. The same biomass samples can be placed into a temperature controlled oven to create ash at the remaining temperature ranges of 450 °C, 500 °C, 550 °C, and 600 °C. As the biomass is known to stabilise in its mass above 450 °C, only two temperature ranges will need to be explored to prove this is true, being 450 °C and 500 °C.

Biomass samples in this case have been collected from ground litter, as there is no requirement for the leaves to be planar for the waveguide measurements. Due to the large mass loss experienced by the biomass at higher temperatures, a large amount of ground litter is required to make a small amount of ash. The resultant ash is turned into a powder where it is then compressed into a waveguide sample holder and measured at the required frequency bands.

Ash created under these high effective exposed temperatures is highly porous by nature. Once the ash has been turned into a powder there is the introduction of compaction; which has a direct effect on the porosity or volume fraction of the measurements inside a waveguide. For example, the more ash that can be compacted into a sample holder the higher the effective permittivity becomes due to the field interacting with more material. To extract an approximate value of the permittivity of an ash particle exposed to each of the effective temperature ranges, the porosity (or volume fraction) of the ash particle must be known. Once this is known, the powdered ash can be sampled at different volume fractions and an approximation of the effective permittivity can be extracted. This extraction cannot be assumed to be linear as the response of powdered materials has been shown to be non-linear and is dependent on particle geometry on the macroscopic level [149-151, 153-156, 171-176]. The measured permittivity values as different volume fraction must then be fitted to what is termed a mixing law which describes the non-linearity extremely accurately over those measured volume fractions. This model is only valid over low volume fractions which are suitable for application in describing ash.
4.5.1 Unified Mixing Law Semi-Empirical Modelling of Powdered Ash at X-Band and Ka-Band

To investigate the relative complex permittivity of ash at higher temperatures, as well as the effects of natural atmospheric moisture absorption, several heating tests were undertaken. In separate incidences, messmate eucalypt and blackwood wattle samples were exposed to the specific temperatures of 450 °C and 500 °C. Messmate eucalypt ash underwent a third investigation at 1000 °C.

In section 3.7.4 it was shown that the expected bulk density for both the messmate eucalypt and blackwood wattle is expected to be in the order of 0.06 g/cm³. In this case, it is important to try and measure the equivalent bulk density within a waveguide. Through trial and error it was found that this amount of ash could not be physically held within the waveguide section. Here, the bulk density is too low to remain within the rectangular shape. The bulk density within a waveguide for which the ash will stay in position and be self-supported is approximately 0.2 g/cm³. By mapping the permittivity at higher bulk density values, a good approximation value of the ash at these lower bulk density values can be made.

In the same way the controlled biomass samples to 400 °C were prepared, ash at these higher temperatures was also prepared. Ground litter leaves of both the messmate and blackwood wattle were collected and placed inside a kiln oven at the desired temperatures. The resultant ash was then passed through a number of fine meshes to produce a fine powder. The resultant powder was then compacted into a waveguide where its mass was recorded. Before measurement, samples remained on a hotplate to limit the amount of moisture absorption. Samples were measured over X-Band and a single sample at Ka-Band, which from the controlled measurements recorded in 4.4.2 is expected to be identical. The resultant permittivity and loss tangent against the bulk density is illustrated in Fig. 104 and Fig. 105 respectively.

In Fig. 104 the permittivity is shown to have a clear trend with respect to bulk density. The two messmate and two wattle samples at 450 °C and 500 °C show extremely similar trends, as was expected based on the bulk density trends measured in section 3.7.4 Regarding the eucalypt sample, if the relative complex permittivity follows a specific polynomial trend based on the volume fraction (f) of a mixture, this would also suggest that the relative complex permittivity is heavily dependent of the bulk density of ash.
Chapter 4 – RF Properties of Fire Ash Particles

Fig. 104 – Effective permittivity vs. bulk density for various ash samples. Average ambient measure temp. 23°C, RH 45%.

Fig. 105 – Loss tangent vs. bulk density for various ash samples. Average ambient measure temp. 23°C, RH 45%.
If this is the case the relative complex permittivity should follow the same trend as the bulk and this can be used to predict what the relative complex permittivity of ash will be after its ignition point (between 450 °C and 500 °C). Based on the approximated bulk density expected for the ash at 450 °C and 500 °C (as illustrated in Fig. 63), a polynomial extrapolation of the trending data can be made. From this polynomial curve the expected permittivity for ash is in the region of $\varepsilon = 1.05$. This expected value can be used to judge the validity of a generalised relative complex permittivity model to be discussed in section 4.7. This is highlighted in Fig. 104 by the dotted line and circle. Again, the ash of the messmate biomass exposed to 450 °C at Ka-band (38 GHz) has shown only a slight drop in its permittivity, which is to be expected from a weakly dispersive medium. This slight drop in the controlled samples was not visible as the samples were extremely thin. The small variation over frequency within these thin samples gets lost in measurement noise. The powdered ash here was 2.8 mm thick, thus allowing for the material to interact with an electric field for a longer duration. This effectively allows for better sample material averaging to take place in the spatial domain. Similar trends are seen in the imaginary component of the permittivity described by the loss tangent in Fig. 105.

The most significant change in the permittivity is seen when ash created at 1000 °C was measured. Here, the permittivity significantly dropped away, which from the known mass loss trends is also expected. Translating this to the permittivity for an ash particle exposed to this temperature range, there is little expected change. Projecting the bulk density into this range, it is estimated to be in the order of $\varepsilon \sim 1.01-1.02$. A comparison between naturally saturated ash and the dry ash exposed at 1000 °C has also been made. Here, a 2.51% (by weight) natural saturation level at 1000 °C was measured and shown to have very little effect on the overall permittivity. Slight variation in the loss tangent was shown, however; this was within the measurement error.

Expanding on these measurements, the data can now be implemented into the unified mixing law. This is achieved by solving Eqn. (20.) for minimum error. The importance of the mixing law is to investigate the approximation of the inclusion permittivity and the depolarisation factor ‘v’ for each of the samples. The resultant mixing laws for each of the samples are illustrated in Fig. 106, Fig. 107, Fig. 108, Fig. 109, Fig. 110 and Fig. 111. The best-fit parameters found for the minimum error case are illustrated in Table 15 and Table 16.
Fig. 106 – Measured ('M') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity of messmate eucalypt ash exposed at 450°C (10GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 107 – Measured ('M') vs. Theoretical ('T') mixing law for both real and imaginary components of the relative permittivity of messmate eucalypt ash exposed at 500°C (10GHz), average ambient measure temp. 23°C, RH 45%.
Fig. 108 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity of messmate eucalypt ash exposed at 1000°C (10GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 109 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity of messmate eucalypt ash exposed at 450°C (38GHz), average ambient measure temp. 23°C, RH 45%.
Fig. 110 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity of Blackwood wattle ash exposed at 450°C (10GHz), average ambient measure temp. 23°C, RH 45%.

Fig. 111 – Measured (‘M’) vs. Theoretical (‘T’) mixing law for both real and imaginary components of the relative permittivity of Blackwood wattle ash exposed at 500°C (10GHz), average ambient measure temp. 23°C, RH 45%.
Table 15: Summary of mixing law results at mid-band frequency (10 GHz)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Freq. (GHz)</th>
<th>v</th>
<th>$\varepsilon_i_{\text{real}}$</th>
<th>$\varepsilon_i_{\text{imag}}$</th>
<th>$\tan(\delta)$</th>
<th>$\rho$ (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt 450°C</td>
<td>10</td>
<td>10.0059</td>
<td>9.38</td>
<td>0.58</td>
<td>0.062</td>
<td>-2.84</td>
</tr>
<tr>
<td>Eucalypt 450°C</td>
<td>38</td>
<td>10.0054</td>
<td>8.59</td>
<td>0.52</td>
<td>0.060</td>
<td>-2.84</td>
</tr>
<tr>
<td>Eucalypt 500°C</td>
<td>10</td>
<td>10.0085</td>
<td>9.41</td>
<td>0.63</td>
<td>0.067</td>
<td>-2.84</td>
</tr>
<tr>
<td>Eucalypt 1000°C</td>
<td>10</td>
<td>10.0515</td>
<td>6.45</td>
<td>0.063</td>
<td>0.01</td>
<td>-2.84</td>
</tr>
<tr>
<td>Wattle 450°C</td>
<td>10</td>
<td>10.0154</td>
<td>9.95</td>
<td>0.64</td>
<td>0.064</td>
<td>-2.84</td>
</tr>
<tr>
<td>Wattle 500°C</td>
<td>10</td>
<td>10.005</td>
<td>8.91</td>
<td>0.40</td>
<td>0.046</td>
<td>-2.84</td>
</tr>
</tbody>
</table>

Table 16: Summary of fitting errors for measurements and mixing model

<table>
<thead>
<tr>
<th>Sample</th>
<th>Freq. (GHz)</th>
<th>$\varepsilon_{\text{eff}}$</th>
<th>Max. § $\varepsilon_{\text{eff}}$</th>
<th>Ave. * $\varepsilon_{\text{eff}}$</th>
<th>Max. + $\varepsilon_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt 450°C</td>
<td>10</td>
<td>±0.025</td>
<td>3.60%</td>
<td>1.53%</td>
<td>7.99%</td>
</tr>
<tr>
<td>Eucalypt 450°C</td>
<td>38</td>
<td>±0.025</td>
<td>2.97%</td>
<td>1.62%</td>
<td>7.39%</td>
</tr>
<tr>
<td>Eucalypt 500°C</td>
<td>10</td>
<td>±0.025</td>
<td>4.26%</td>
<td>1.69%</td>
<td>9.64%</td>
</tr>
<tr>
<td>Eucalypt 1000°C</td>
<td>10</td>
<td>±0.025</td>
<td>1.01%</td>
<td>0.60%</td>
<td>2.26%</td>
</tr>
<tr>
<td>Wattle 450°C</td>
<td>10</td>
<td>±0.025</td>
<td>3.43%</td>
<td>1.73%</td>
<td>8.20%</td>
</tr>
<tr>
<td>Wattle 500°C</td>
<td>10</td>
<td>±0.025</td>
<td>5.91%</td>
<td>2.33%</td>
<td>13.40%</td>
</tr>
</tbody>
</table>

* Dielectric measurement error from Vector Network Analyser
§ Maximum percentage error between empirical curve and measured points
** Overall average percentage error between empirical curve and measured points
+ Maximum percentage error between $\varepsilon_i$ and $\varepsilon_i$ determined from each data point for optimal solution

As shown in Table 15 both the depolarisation factor ‘v’ and the estimated inclusion relative complex permittivity in the 450°C and 500°C samples for both genera are extremely similar. The change here is in the high temperature eucalypt sample at Eucalypt 1000°C, where the inclusion permittivity is expected to drop to $\varepsilon = 6.45+j0.063$.

4.6 Micro Computer Tomography EM Simulations

As discussed in section 0, the inclusion of the relative complex permittivity is paramount in accurately determining mixing laws for the ash. Presently, this inclusion or base relative complex permittivity has been characterised by optimising the mixing law models for the least error. This approach allows for the models to be described accurately for low volume fractions, however; at high concentrations this will become invalid as the relative complex permittivity becomes more dominant in the mixing law. To investigate the inclusion...
permittivity of ash, an electromagnetic back-optimisation approach was implemented. Here, samples that were prepared as part of the controlled temperature measurements outlined in section 4.4.2 were scanned using a microcomputer tomography (MicroCT) technique. The cross-section images created after the back projection method were again imported into Avizo 6, where they were stitched together to create accurate 3D models of the samples internal cell structures.

These 3D models were then imported into CST Microwave studio and analysed for their electromagnetic properties. A total of three models per temperature range up to 400 °C were investigated to help identify the effects of variations in the structures on the inclusion relative complex permittivity. An example of a 3D model produced from the MicroCT scans of the messmate eucalypt can be seen in Fig. 112. Using this approach for investigating the inclusion permittivity has one particular advantage, this being the ability to take into account the effects of the variable surface structure of the material. The deviation in the porosity of measured and MicroCT ash shown in section 3.7.4 will be assumed to fall within an acceptable deviation from the median porosity value.

To achieve the back-optimisation approach, the measured relative complex permittivity values were firstly used to create a baseline model. Here, a block of material was assigned the same permittivity and thickness as those parameters determined from measurements. The values of the measured relative complex permittivity and loss tangent of the biomass samples at each exposed temperature range was then assigned to this block of materials and these can be observed in Fig. 113. The simulation model takes into account the measured thickness used to extract the permittivity in the NWR method, thus giving a full representation of the bulk material. The S-Parameters were de-embedded to the thickness of the material and the resultant S-Parameters stored as a reference for the optimisation.
The block of material used to represent the measured ash was then substituted for the 3D MicroCT model. The stored de-embedded S-Parameter data was then used to setup a trust region optimisation, whereby the assigned permittivity and loss tangent of the MicroCT 3D model could be altered. Next, the optimisation was instructed to change the permittivity and loss tangent of the porous MicroCT model until the S-Parameters reached an acceptable agreement with the baseline model. The error threshold was set to 1% variation, however all simulations achieved matching well below this level. Both the resultant inclusion relative complex permittivity and optimisation error are illustrated in Fig. 114 and Fig. 115 respectively.

Demonstrated by the outcomes of the optimisation is an increase in the relative complex permittivity, beginning at 150 °C and slowly increasing in temperature. This increase in the inclusion permittivity can be explained by two phenomena; the first being the absorption of moisture into the biomass and the second is a change in the elemental breakdown. The rate of absorption and the eventual saturation point has been shown in section 3.7.3 to be significant within biomass exposed to temperatures above 250 °C. The elemental breakdown of the eucalypt biomass has been shown to possess more oxygen than carbon as the temperature increases, although carbon is still a dominant player up to 400 °C. It is likely that the inclusion of moisture will contribute slightly more to the inclusion permittivity than changes in the material composition beyond this temperature range. Separating the effects of moisture and elemental composition is difficult as they both change with temperature.
Fig. 113 – Measured permittivity and loss tangent for the messmate eucalypt samples
Fig. 114 – Inclusion/solid permittivity and loss tangent of ash predicted from the back optimization process carried out in CST MWS.
The slightly higher inclusion permittivity for the unburnt case is likely to fall inside the statistical variation expected for the biomass. From the knowledge gained about the moisture absorption rates and elemental composition, the material should remain relatively consistent up to 250 °C. Only seven samples could be scanned using the MicroCT technique, therefore a conclusive explanation cannot be formed from these results. To give a definitive answer, multiple MicroCT scans are required to ascertain a standard deviation for the inclusion permittivity.

Fig. 115 – Optimization matching error
Chapter 4 – RF Properties of Fire Ash Particles

4.7 A Generalised Fitted Relative Complex Permittivity Model for Ash

The measurement of the effective relative complex permittivity of ash has been shown to trend with temperature. It has also been demonstrated that this trend is common within the same genus and possibly between different genera. With the assumption that this will be the case for all carbon-based organic life, a generalised relative complex permittivity model can be created. This model, (representative of the change in the relative complex permittivity with respect to the effective exposed temperature of the biomass), must also be described over a wide bandwidth. Measurements have shown that the real part of the permittivity does not significantly change (8 - 12 GHz) to Ka-Band (26.5 – 40 GHz).

The real part of the relative complex permittivity directly corresponds to the reflectivity of a material and is the major contributor to the refractive index (see Appendix A). Conversely, the imaginary component represents the loss within the material. Describing the real component of the relative complex permittivity is significantly more important than describing the imaginary part due to its contribution in defining the reflectivity of a material. As shown by the measured loss tangent of the biomass outlined in section 4.4.2, the imaginary component has a relatively larger variation compared to the real component. This is inherently the result of measuring thin samples, which in the case of biomass is unavoidable.

Furthermore, by definition the relative complex permittivity should follow a similar trend to the volume fraction of a material. As shown by the unified mixing law, a reduction in the amount of material present within a unit volume will result in a lower overall effective permittivity. It has been shown that the bulk density follows a similar trend to that of the normalised mass loss curve.

With the information garnered on bulk density and the approximate solid density of ash for amorphous carbon, a volume fraction estimation can be obtained. This has been calculated in Eqn. (22).

\[
\frac{V_{f_{22c}}}{V_t} = \frac{\rho_{bulk}}{\rho_{solid}} = \frac{0.8}{2.267} = 0.35
\]

(22)
As this value will change with respect to bulk density, an expression for the volume fraction can be derived. This however, is better suited in relation to the normalised mass loss of the material. With the knowledge that bulk density is proportional to the normalised mass loss curve, a scale function can be used to model the volume fraction of the biomass. This can be achieved using Eqn. (23).

\[
V_f = V_{f_{22^\circ C}} - (V_{f_{22^\circ C}} \cdot \frac{m_{\text{norm}}}{100})
\]  

(23)

Once the volume fraction is known for a generalised model, the unified mixing law can be implemented to describe the effective permittivity of the biomass at any known effective exposed temperature point. To use the mixing law correctly, the inclusion or solid permittivity of the ash must be known. This value can be obtained from the back optimisation values determined from the MicroCT scans of eucalypt biomass, as demonstrated in section 4.6. As moisture affects the outcome of those results at higher effective exposed temperature ranges, the best representation of the inclusion permittivity can be gained from the unburnt sample. Here, the median value obtained from all three of the unburnt back-optimised models is given by Eqn. (24).

\[
\varepsilon_{t_{22^\circ C}} = 5.75 + 0.574i
\]  

(24)

Furthermore, it is known from the elemental breakdown explored in section 3.7.2 that the percentage of elemental carbon remains consistently high up to 400 °C. If it is assumed that the inclusion permittivity remains consistent up to 400 °C, the effects of the inclusion permittivity may also be extended to higher temperatures. This is a valid assumption, as the background medium (in this case air) becomes the dominant mixing medium. The inclusion permittivity estimated by the optimised unified mixing law for the uncontrolled case shows similar agreement with this assumption, as the real part of the inclusion permittivity was estimated to have risen to \( \varepsilon = 6.3 \).

Using Eqn. (20), a generalised effective permittivity based on measured data for ash over the exposed temperature range to 600 °C is illustrated in Fig. 116.
Fig. 116 – Permittivity and loss tangent predicted from using the unified mixing law.
Here, the real part of the complex effective permittivity corresponds to the measured effective relative complex permittivity of ash measured in section 4.4.2. Conversely, the loss tangent is shown to be over estimating the correct value by an approximate factor of \( \tan \delta = 0.01 \). The error in the loss tangent is a result of uncertainties in the imaginary component of the relative complex permittivity which was expected due the thin biomass samples. A small adjustment to the models has been made to align the imaginary component with the measured data. The resultant corrected inclusion permittivity is given by Eqn. (25). The resultant corrected loss tangent model is illustrated in Fig. 117.

\[
\hat{\varepsilon}_{12}^e = 5.75 + 0.49i
\]

(25)

![Graph showing corrected loss tangent predicted from using the unified mixing law](image)

*Fig. 117 – Corrected loss tangent predicted from using the unified mixing law.*

The complete generalised model shows relatively good agreement with the measured data. The RMS error for the model again the measured data at X-Band is illustrated in Table 17.
### Table 17: RMS Error between measured and unified mixing law to 400°C at 10GHz

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>*Mixing Law</th>
<th>$\varepsilon'$ RMS Error</th>
<th>$\varepsilon''$ RMS Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>UM</td>
<td>0.038</td>
<td>0.0270</td>
</tr>
<tr>
<td>150</td>
<td>UM</td>
<td>0.164</td>
<td>0.0111</td>
</tr>
<tr>
<td>200</td>
<td>UM</td>
<td>0.147</td>
<td>0.0171</td>
</tr>
<tr>
<td>250</td>
<td>UM</td>
<td>0.138</td>
<td>0.0113</td>
</tr>
<tr>
<td>300</td>
<td>UM</td>
<td>0.262</td>
<td>0.0146</td>
</tr>
<tr>
<td>350</td>
<td>UM</td>
<td>1.642</td>
<td>0.0160</td>
</tr>
<tr>
<td>400</td>
<td>UM</td>
<td>0.160</td>
<td>0.0144</td>
</tr>
</tbody>
</table>

*UM – Unified Mixing Law

### 4.7.1 Generalised Relative Complex Permittivity with Moisture Inclusion

The generalised relative complex permittivity model does not take into consideration the effects of moisture. The inclusion of moisture will greatly affect the overall relative complex permittivity of the ash due to the high relative complex permittivity of water. The inclusion of moisture introduces a number of complexities for which mixing laws need to model. There are four areas identified within ash where these complexities may cause issues with common dielectric mixing laws [153-156, 168, 177-185]. The first relates to the treatment of the particles geometry within ash, the second and third relate to the interaction of free water and bound water respectively, while the final complexity deals with the interaction of residual salts within the ash (i.e. NaCl, KCl) which can be greater than 1% w/w in some species [84-91].

The structure of ash, demonstrated by its large depolarization factor ‘ν’, cannot be considered spherical in nature. Furthermore, the effects on the depolarized state of the ash is expected to change with the inclusion of water. This can be explained by considering where the water will consolidate inside the remanent cell structure of the ash. At low moisture contents it is expected that water will form on or inside the ash structures effectively increasing their permittivity. At these low moisture contents a similar depolarized state to that of the dry case should be seen (i.e. ν~10). Once the moisture content has saturated the ash it can be hypothesized that small regions of pure water begin to form between neighbouring particles. Due to the high surface tension properties of water these are likely to be partly spherical like in nature. Thus it is likely the depolarisation state to transition to a smaller number as the amount of water is increased. Finally, the case arises when the mixture is completely saturated with a water/ash mixture. Under this condition the effects of moisture can be characterised by taking standard Debye dispersive models for water and re-
substituting it into the unified mixing law. Here, particular attention must be given to the depolarisation factor ‘\(v\)’ which will trend even lower until the medium can be effectively described by a Maxwell-Garnett mixing law (i.e. \(v \approx 0\)).

Using a standard Debye dispersion model (See Eqn.( 21)) for water such that \(\varepsilon_{\infty} = 78.4\), \(\varepsilon_{\infty}' = 3.1\) and \(\tau = 8.27 \times 10^{-3}\) ns (at 25 °C), a broadband relative complex permittivity model can be created. An extended semi-empirical Debye model with respect to temperature has been included in Appendix A. This model for water under the given conditions is illustrated in Fig. 118. At 10 GHz the relative complex permittivity of water from the Debye model is \(\varepsilon_{\text{water}} = 61.8 + 31.1i\). Under this condition the relative complex permittivity of water is known as ‘free’ water. The inclusion of water however has in recent years been found to differ from that expected at low concentration levels.

This has been termed a bound water state. It has in recent years been attributed as one of the missing links in mixing laws [168, 177-185]. Bound water is formed when water, a highly polar material, interacts with other polar or charged molecules via hydrogen bonds. The consequence of this molecular interaction has a direct effect on the relaxation time (\(\tau\)) of water as a function of its distance from a bonded interface [168, 177-185]. The net change in
the relaxation factor significantly alters the complex permittivity of bound water to that of free water. However, the fundamental forces causing the interactions of bound water within different materials is still being developed [168, 177-185]. The existence of bound water in soil for example has been noted to be stronger in clay compared to sand and silt [183]. Also linked to bound water is the inclusion of salts which become dissolved solids that directly increase the imaginary component of free water. The dissolved ions will also have weak hydrogen bonds to surrounding water molecules.

As little is still known about the cause of the complex permittivity of ash on an atomic scale, a fully descriptive mixing law cannot be implemented. However, using an empirical based approach we can correct mixing laws for the response of a material with the inclusion of water. Two mixing laws have been analysed for their performance in predicting the trend of water inclusion in ash. These mixing laws include a substitute unified mixing law, and a multi-phase Maxwell-Garnett mixing law (see Eqn. (26)). Implementation of more advance four phase mixing laws such as the Maxwell-De-Loor mixing law (see Eqn. (27)) will be left for future analysis when sufficient knowledge on weather bound water is applicable to ash and to what degree is known [168, 177-185]

\[
\frac{\varepsilon_{\text{eff}} - \varepsilon_e}{\varepsilon_{\text{eff}} + 2\varepsilon_e} = \sum_{n=1}^{N} \frac{\varepsilon_{i,n} - \varepsilon_e}{\varepsilon_{i,n} + 2\varepsilon_e}
\]

\[
\varepsilon_{\text{eff}} = \frac{3\varepsilon_s + 2(f_w - f_{bw})(\varepsilon_w - \varepsilon_{bw}) + 2f_{bw}(\varepsilon_{bw} - \varepsilon_s) + 2(n - f_w)(\varepsilon_e - \varepsilon_s)}{3 + \left(\frac{\varepsilon_e}{\varepsilon_{bw}} - 1\right) + f_{bw}\left(\frac{\varepsilon_s}{\varepsilon_{bw}} - 1\right) + (n - f_w)\left(\frac{\varepsilon_s}{\varepsilon_e} - 1\right)}
\]

(26)

(27)

In the multiphase Maxwell-Garnett mixing law given in Eqn. (26) \(\varepsilon_{\text{eff}}\) is the effective permittivity of the mixture, \(\varepsilon_e\) is the permittivity of the host material (air), \(\varepsilon_{i,n}\) is the complex permittivity of the \(n^{\text{th}}\) inclusion material (ash, water, etc.) and \(f_v\) is the volume fraction of the \(n^{\text{th}}\) inclusion material. In the Maxwell-De-Loor mixing law given in Eqn. (27) \(\varepsilon_s\) is the solid inclusion permittivity (ash), \(\varepsilon_w\) permittivity of water, \(\varepsilon_{bw}\) permittivity of bound water, \(\varepsilon_a\) permittivity of air, \(f_v\) is the volume fraction of air, \(f_w\) is the volume fraction of water, \(f_{bw}\) is the volume fraction of bound water and \(n\) is the porosity of the mixture. The form of the Maxwell-DeLoor mixing law can be seen to be particularly problematic to solve if the effect
of bound water is unknown. Further to this is the inability to treat changes in the
depolarisation factor in both these mixing laws.

Many dielectric mixing laws at their heart are polynomial functions, which in many
materials successfully describe contributions of each of the constituent phases.

The approach for modelling the ash/water mixture considered here has been to implement
a second two phase unified mixing law assuming the $\varepsilon_{\text{eff}}$ of the air/ash medium acts as a
single inclusion material. Mathematically, under a Maxwell-Garnett approach, this leads to an
incorrect implementation of the mixing law. However, the inclusion of the depolarization
factor ($v$) allows for the development of a regression function to correct the slope of the
unified mixing law to best fit the measured data. For a multiphase mixing law this type of
correction is not possible as the constituent terms are set with a predetermined depolarised
state. This approach becomes a semi-empirical mixing law.

To analyze these effects and to map the response of larger moisture contents within the ash
samples, a number of permittivity measurements were made using the 1000°C ash sample.
The measurement procedure was as follows; powdered ash was dried on a hotplate at 400°C
for 30 minutes, the hot ash was then compressed into a waveguide at an arbitrary bulk
density (in this case $\sigma_{\text{bulk}}=0.895$ g/cm$^3$). These first steps were critical to avoid the re-
absorption of moisture within the sample. To aid in this the sample holder was placed on a
200°C hotplate while the permittivity measurements were prepared. Also, by compressing the
hot ash sample within the sample holder, re-absorption of moisture is restricted to the
exposed surfaces of the sample. The sample was then taken off the hotplate and its complex
permittivity measured. Once this measurement was completed, the sample was once again
weighed to give an indication of the amount of moisture absorbed by the sample. With some
trial and error the moisture content was suppressed to 0.42% w/w which forms part of the
correction procedure for the effective response of the ash.

Deionized water was added to the sample within the holder to approximately 25.1% w/w.
The sample was left to completely saturate. Once sufficient time was given to the sample to
saturate, the permittivity as measured followed by another measurement of its mass. The
resultant mass loss over the initial saturation period was approximately 4.65%, which forms
the upper limit of 20.4% w/w for these measurements. Following this, the wet sample was
then slowly warmed using a low temperature hotplate to remove a small portion of its water
content. The sample was again placed inside the waveguide and its S-Parameters measured.
Here, a measurement was only saved once the S-Parameters were stable. The process was
repeated consecutively until the mass of the original dry ash sample was reached. Fig. 119
Fig. 119 – Measurement of the effective complex permittivity of powdered ash with respect to different moisture contents by weight. Bulk density of dry ash sample within waveguide holder was $\rho_{\text{bulk}} = 0.895 \text{ g/cm}^3$ (atm. temp. = 21.5°C, RH = 37.5%)
Illustrated again is the almost linear response of the effective complex permittivity of the ash with moisture inclusion around 1-2% w/w. Here, the upper limit of this almost linear zone is slightly reduced compared to those seen in Fig. 104 and Fig. 105 to approximately 1.65% w/w. This slightly lower level is most likely due to the higher bulk density value of the original powdered ash sample thus the amount of water per unit volume is increased. Using the knowledge of how the relative complex permittivity trends with respect to moisture content, an extension to the unified mixing law can be investigated. The results of this investigation have been illustrated in Fig. 120. The results of the substituted unified dielectric mixing law with respect to different depolarization values and the empirically determined regression function is given in Eqn. (28).

\[ v(f_v) = 1.83 f_v^{-0.7} \left\{ f_v | f_v > 0, f_v \leq (1 - f_{ash}) \right\} \]

Fig. 120 – Performance of the substituted unified mixing law with respect to measured and predicted permittivity. \( e_v \) is measured high volume fraction data, \( e_h \) is measured low volume fraction data, \( e_w \) is the relative complex permittivity of water under various conditions and \( v \) is the depolarisation factor where \( v(f_v) \) is an empirically derived regression curve.
The complex permittivity of water used in the mixing analysis was based on the revised empirical based Debye model found in Appendix A. The resultant RMS errors for the each curve for both the real and imaginary component is given in Table 18. Further to this is the RMS error for the equivalent multiphase Maxwell-Garnett mixing law. The empirically determined regression curve for $v$ shows very good agreement with the real component of the measured data.

<table>
<thead>
<tr>
<th>Table 18: RMS Error between measured and unified mixing law with moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. (°C)</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>61.8+31.1i</td>
</tr>
<tr>
<td>61.8+31.1i</td>
</tr>
<tr>
<td>61.8+31.1i</td>
</tr>
<tr>
<td>61.8+36.1i</td>
</tr>
<tr>
<td>61.8+31.1i</td>
</tr>
<tr>
<td>61.8+31.1i</td>
</tr>
</tbody>
</table>

*UM – Unified Mixing Law
*MG – Maxwell-Garnett Mixing Law

There is a slight discrepancy in the imaginary component which is over predicted, however it still give the best RMS error for predicting the complete complex response.

It is evident from the analysis of the different values of $v$ that the depolarization state of the ash particle still influences the field displacement over the full volume fraction range. This is particularly highlighted in the RMS error for the three phase Maxwell Garnett mixing law (MG-3P) which poorly described the ash. The regression described the real component of the ash well however there is a small divergence in the imaginary part. From the analysis of the different depolarization factors the best fit was achieved with a slightly conductive water content with a depolarization factor $v=3$. The discrepancy between the desired $v$ for the real and the imaginary may be an indication that the bound water or other physical attribute of the ash/water mixture are changing the displacement of the internal field. There effects are outside of the scope of this dissertation and will need further investigation to understand the true physical interactions on the atomic level. Finally, the analysis of the effects of constant moisture content on the complex permittivity as predicted from the substituted unified mixing law (with $v(f_v)$) are illustrated in Fig. 121 and Fig. 122 for X-Band and Ka-Band respectively.
Fig. 121 – Permittivity and loss tangent predicted form the substituted unified mixing law for ash at various exposed temperature and moisture contents. Analysis taken for a case at 10GHz, 21.5°C.
Fig. 122 – Permittivity and loss tangent predicted form the substituted unified mixing law for ash ate various exposed temperature and moisture contents. Analysis taken for a case at 38GHz, 21.5°C assuming the change the small changes in permittivity between X-band and Ka-Band are neglected.
4.8 Conclusion

This chapter has focused on exploring the complex permittivity of ash with respect to the effective exposed temperature. It has provided an in-depth understanding of both controlled and uncontrolled samples, which has aimed to bridge some of the gaps present in the current knowledge. It was demonstrated that ash produced under controlled temperatures (from both the eucalypt and acacia genera) displays identical effective complex permittivity at X-Band frequencies. Using the eucalypt genus as an example, the complex permittivity of the controlled samples was also extracted up to Ka-Band. The response of the material between X-Band and Ka-Band was shown to be quite linear. The most noticeable discrepancy over the two frequency bands was that the loss tangent which slightly increased at the higher frequency bands. To understand the average complex permittivity, further investigations were made using uncontrolled samples to extract a value for the average complex permittivity of powdered ash. The linearity of the complex permittivity over frequency was again demonstrated. It was shown here that although the material acts in a similar way under controlled conditions, the flammability of the material begins to play a major role in the final effective complex permittivity.

Taking into account the volume fraction of the ash, it was also shown using the unified mixing law that the smaller constituents of ash all act identically between many types of genera. The depolarisation factor from the measured effective complex permittivity was found to be approximated by $v = 10$. This was the case for all six genera tested. The cause of the higher than normal depolarisation factor was attributed to the remanent cell structures present within biomass. This forms ash with more planar-type structures. The planar-type structures, along with cylindrical and spheroidal-shaped particles combine to give a more linear response than a pure, spheroidal-type mixing law such as Maxwell-Garnett. The inclusion permittivity to satisfy the unified mixing law was also extracted. This was checked against a back-optimised MicroCT model imported into CST microwave studio.

The resultant inclusion complex permittivity along with the porosity of ash measured in Chapter 3 were then used with the unified mixing law to create a generalised effective complex permittivity model. Using an inclusion permittivity of $\varepsilon = 5.75+0.574i$, the mixing law created a model that showed good agreement with the controlled effective permittivity results. The loss tangent however, was slightly overestimated compared to the measured...
values. Shifting the inclusion permittivity to $\varepsilon = 5.75 + 0.48i$ provided a much better agreement to the measured results.

An extension of the unified mixing law to include moisture was then implemented. It was shown that an inclusion permittivity of up to 30% w/w provided a high permittivity value of approximately $\varepsilon = 21$. Similar effective permittivity values were seen in the uncontrolled powdered ash samples measured in section 4.5. Within the literature relating to radar observations of smoke plumes, specifically those relating to polarimetric measurements [54, 55], the expected permittivity required to fit the measured reflectivity of the radar has been estimated to be in the order of $\varepsilon = 15$. Under the given generalised effective complex permittivity model with the inclusion of moisture, the realisation of a particle reaching the saturation levels required to match this is in the order of 25% w/w. Based on the projected absorption rates characterised in section 3.7.3, this will require an absorption time in excess of ten minutes in dry conditions (assuming moisture is available.) Currently, there is little knowledge on the super-saturation levels of these larger ash particles. Smaller smoke particles on the micrometre scale have been measured to be in the order of 1% super-saturation [68, 69, 123]. It must also be noted that the absorption rate decreases with lower effective exposed temperature.

Finally, colour-matching techniques were used to extract an approximation of the effective exposed temperature distribution. The effective temperature distribution can then be used as a link to provide knowledge of the effective complex permittivity distribution of ash particle arising from bushfires. The peak distribution of the ~4000 ash particles analysed for a moderate temperature fire was found to form between 400°C and 450°C, indicating uneven heating of the biomass. This is to be expected, as the fire does not contain sufficient heat to remove all the carbonaceous components. The formations of the lower effective exposed temperature distributions were analysed and found to possibly arise from the partial pyrolysis or carbonaceous region formations commonly found during the burning of biomass. To further support this hypothesis, a 3D probability distribution function was created between/for the effective exposed temperature, projected area and aspect ratio. The smaller effective temperature distributions were shown to follow similar trends to PDF’s measured for the projected area and aspect ratio characterised in Chapter 3. The formation of smaller particles with high carbon content fit with observations of the types of ash created within fires. This further highlights that the matching method provides a good approximation of the effective exposed temperature.
The knowledge gained about ash within this chapter has provided answers to the second, third and fourth research questions. The analysis of the biomass has provided a model that describes how the permittivity changes between different genera and with respect to the energy output of the biomass. The analysis was carried out on the eucalypt and acacia genera showing similarities in the complex permittivity against exposed temperature. As these two genera form the highest populated plant and tree species within Australia, they provide a good fundamental knowledge of how ash from fires will interact with electromagnetic waves. Finally, the implementation of the unified mixing law provided a means of accurately describing the effective complex permittivity with respect to the effective exposed temperature and moisture content.

With the knowledge gained in Chapters 3 and 4 there is sufficient information to begin analysing the reflectivity of ash. Using a number of measurement techniques and simulation models, the individual radar cross-section can be extracted. Extending this to the reflectivity, simulations can be used to study and isolate the scatter created from ash particles alone. The final chapter of this dissertation will be dedicated to understanding some of the fundamental scattering properties of ash, both on a particle level and as a dispersed medium.
Chapter 5 – Radar Cross-Section and Simulated Reflectivity

5.1 Introduction

Chapters 3 and 4 of this document presented an extensive investigation of the geometric, physical, dynamic and relative complex permittivity values of forest fire ash. The analysis of the eucalypt and acacia genera with the inclusion of common species has shown some remarkable similarities. Furthermore, the complex behaviour of ash as a material has also been highlighted. The in-depth analyses of ash in Chapters 3 and 4 have provided sufficient data to begin to analyse the radar cross-section and hence, the reflectivity of ash over a wide frequency range (1 - 40GHz). This is essential when defining the expected radar reflectivity for radar system design and for the development of an inverse scattering model.

As observed in various radar recordings of fires, a number of different scattering sources co-exist. This chapter will focus on the expected reflectivity of statistically correct ash particles as an isolated medium within smoke plumes. It should be noted that observations of smoke plumes using weather radar cannot distinguish these individual scattering sources, and only the total scattered power in various polarisation schemes can be measured. As part of the research roadmap outlined in Fig. 8, there is sufficient information to identify the expected radar cross-section of an individual ash particle. This can be achieved using traditional radar cross-section measurement techniques. The measured radar cross-sections of ash may also be compared with simulated particles of equivalent cross-section and permittivity, based on the proposed generalised model created in Chapter 4.

The analysis of the individual radar cross-sections of ash particles then leads to the ability to analyse the total volumetric reflectivity, as characterised by the research roadmap illustrated in Fig. 7 and Fig. 8. The reflectivity can be measured using dynamic cross-section
measurements and simulated to form a fundamental understanding of the scatter for creating an inverse model. This dissertation will focus on analysing the reflectivity factor with respect to particle concentration. This relationship is important for determining a correlation between the amount of biomass consumed within a fire and the resultant reflectivity. Secondary to this is the analysis of traditional polarimetric coefficients such as the differential reflectivity, linear depolarisation ratio, and co\cross polarisation reflectivity. In the case of planar ash particles that form within the eucalypt and acacia genera, their typical descending dynamic modes can also be analysed. This is important, as the reflectivity will change based on the respective incident angles of a propagating electromagnetic field. The reflectivity can be compared to traditional theoretical reflectivity models, such as those used in weather radar for analysing precipitation.

5.2 Radar Cross-Section (RCS) Measurements of an Ash Particle

The radar cross-section of an object describes its scattering ability towards a radar system. Its general definition is given by Eqn. (29).

\[
\sigma = 4\pi R^2 \frac{|E_s|^2}{|E_0|^2}
\]

(29)

where \( R \) is the one-way range, \( E_s \) is the scattered electric field strength and \( E_0 \) is the incident field strength. The premise of the RCS relies on two main constituent properties of an object, namely its geometric shape and RF material properties \( (i.e. \text{ permittivity and permeability}) \). As highlighted in previous chapters, these two properties are related and cannot be separated unless a fundamental analysis of each area is conducted.

There are a number of ways to measure the RCS of an object. These methods vary based on the size of a target of interest and measurement capabilities. Traditionally, all free space RCS measurements are performed within the far-field. For electrically large objects, this may require measurement ranges that are hundreds of meters long to satisfy the general far-field definition given by Eqn. (30).
where $R_{ff}$ is the required far-field range, $D$ is the largest cross-sectional dimension of a target or antenna and $\lambda$ is the corresponding wavelength. The cross-sectional dimension must be considered for both the transmit antenna, as well as the object under test due to its reflected far-field properties. If the far-field range cannot be achieved in a compact range such as an anechoic chamber, then a near-field to far-field transformation is required. This conversion can be carried out using microwave imaging techniques such as microwave tomography.

The measurement of RCS can also be achieved using an exact or relative type measurement. The exact evaluation of the RCS is achieved by characterising all terms within the radar range equation to solve for the radar cross-section (see Appendix A). A relative measurement is achieved by analysing the scattering from shapes of known RCS to characterise a measurement setup. The RCS of an unknown target is then measured and the relative scattering corrected for the measurement setup correction coefficient ($k$).

Considering a small target that satisfies the far-field requirement within many compact ranges (such as those imposed by ash particles), the limiting far-field length is bound by the cross-sectional dimension of the test antenna aperture. In a practical case where wideband antennas are employed, these far-field distances are typically some meters in length. Therefore, considering the known geometric and RF material properties of ash, the sensitivity of the measurement is improved over free space. An alternative means of measuring the RCS of a small target can be implemented using a waveguide method. Here, the closed environment of the waveguide naturally offers the best signal to noise ratio [186-192]. These compact waveguide ranges can also be used to study polarimetric scatter if small targets [186-192].

The measurement of the RCS within a waveguide differs slightly to that of a free-space approach. In the case where a VNA is used to measure the S-Parameters, the RCS can be calculated based on the $S_{11}$ parameter. It is also important to understand the power spectral density of a waveguide to help clarify the positioning of a target to be measured. This is because the power spectral density is not constant over the cross-section of a waveguide. An illustration of the power spectral density of a WR-90 waveguide at 10GHz is seen in Fig. 123.
As demonstrated by Fig. 123, the ideal placement of an object inside a waveguide is in the centre of the broad wall where the power spectral density is largest. Irrespective of its placement along the short wall structure, the RCS will be identical. The RCS can be extracted by solving Eqn. (31) [193]. This is a simplified version of the radar range equation where the measurement correction coefficient \( k \) is used to describe the gains and losses of a waveguide network.

\[
\sigma = |\Gamma|^2 \cdot k = |S_{11}|^2 \cdot k
\]

The ratio of the received power \( (P_r) \) to the transmitted power \( (P_0) \) is described by the \( S_{11} \) parameter, while the correction coefficient \( k \) can be determined by using objects of known RCS. In this particular case, the RCS standards used to calibrate the setup comprised of metallic ball bearings of various sizes ranging from 0.99 mm to 3.49 mm in diameter. Before the correction coefficient could be measured, the waveguide was pre-calibrated on the VNA to remove unwanted reflections. This was achieved using a TRL calibration identical to that used to measure the relative complex permittivity of ash.
Fig. 124 – Waveguide RCS measurements setup showing a) sample holder with calibration standard in waveguide HP matched terminations, b) Assembled waveguide RCS setup and c) mounting of the medium (M) and large (L) disks in waveguide. Axis systems for RCS measurements also illustrated with respect to incident field ($\mathbf{E}^i$) angles ($\theta$ and $\varphi$).
The sample holder comprising of a small Rohacell foam block with a small patch of
double-sided tape position on the underside. The tape was used to hold the foam block within
the waveguide. A second square of double-sided tape was placed on the upper broad wall to
allow the ash particles being tested to hang vertically under gravity. The sample holder (with
the inclusion of the Rohacell block and tape) must be incorporated as part of the TRL error
model. An illustration of the RCS waveguide measurement setup is shown in Fig. 124.

Once the TRL calibration is complete, the two ports of the VNA are de-embedded to a
known reference plane. The magnitude of the $S_{11}$ as shown in Eqn. (31) is important RCS of
an object. The phase has not relation other than providing range information about the
scattering object. As the ports of the waveguide have been calibrated and de-embedded close
to the target under test, the phase angle provides not useful information about the RCS of the
target. Two different sized ash samples were used for measuring the RCS trends of ash with
respect to the exposed temperatures. The first sample set is labelled as L-Disks, representing
the large disks of approximately seven millimetres in diameter. The second sample set is
labelled as M-Disks, which are medium sized disks occupying half of the waveguide’s short
wall length at 4.70 millimetres. Both diameters were chosen arbitrarily, resulting from the
available hole-punch sets made. Both samples are illustrated in Fig. 124. Samples were taken
from dried messmate eucalypt leaves prepared identically to those used in the controlled
permittivity measurements in Chapter 4. The disks were firstly hole-punched from the dried
biomass and then exposed to each temperature range. As demonstrated in section 3.7.1, this
induces a reduction in both the cross-sectional size of the biomass and the relative complex
permittivity. The L-Disks after exposure and the resultant measured RCS can be observed in
Fig. 125.

The samples were measured at their broadside only (i.e. the orientation with highest
surface area) facing perpendicular to the traveling E-field as illustrated in Fig. 124. It should
be noted that the disk structures of the ash significantly reduce in RCS at other orientations
angles (i.e. when the disk is rotated). Observing images of the exposed disks in Fig. 125, the
450°C disk is seen to contain some carbonaceous material. At this temperature range, most
carbonaceous material should be removed. This error is due to the material not evenly heating
to remove all the carbon content, thus its exposed effective temperature must be corrected.
Using the image processing technique and colour-matching method, its effective exposed
temperature has been determined to be approximately 441°C. A comparison between the
exposed temperature of all disks and the correlating temperature predicted by the image
processing technique is illustrated in Table 19. This again demonstrates how well the matching technique is able to predict the temperature of ash based on its colour.

![Graph showing RCS vs. Frequency](image)

**Fig. 125 - Measured RCS of L-Disks of messmate eucalypt ash at various temperatures. Samples of starting diameter \(d \approx 7 \text{ mm} \). Image of exposed disks illustrated at top (from left to right 22 °C to 500 °C)**

The measured RCS results illustrated in follow a downwards trend. This is consistent with the trend measured in the relative complex permittivity of ash with respect to its effective exposed temperature in Chapter 4. The equivalent measured RCS for the M-Disks is illustrated in Fig. 126. Here, the RCS shows a slightly different trend compared to the L-Disk. Considerations must also be made to the slight variation in the cross sectional and changes in the localised relative complex permittivity of each disk.

As illustrated by the two figures there is a clumping of the RCS at lower temperatures (<200 °C). This clumping can be explained by the low change in the permittivity and considering that the known variance in the permittivity over this range as demonstrated in section 4.4.2. Beyond 200 °C the RCS falls constantly with temperature, which is clearly demonstrated in the L-Disks sample set which has been measured to 500 °C. At these lower permittivity values the scattering become more sensitive to the variation as the material trends...
towards air. This is seen by the large reductions in the scattered field with increases in the effective exposed temperature.

The chosen disk areas closely represent those ash particle which have been shown to exist in open fires. Here, they form a smaller concentration of the overall population of ash particles expected to be produced from fires. The analysis of both RCS measurements demonstrates the low overall RCS of the ash particles.

The RCS of a disk over a wider frequency range is expected to show a logarithmic shaped trend. Due to the limited frequency range of X-Band, the RCS appears quite linear. In both cases, the RCS of the L and M-Disks have similar gradients/slopes in reference to the trend of the RCS over frequency illustrated in Fig. 125 and Fig. 126. If the RCS is assumed to be linear with frequency the gradient of the lines has a mean value of approximately 5.35 over all temperature ranges. This shows that the RCS measurements are consistent between the two size ranges measured. This gradient along with the projected area of the disks can be implemented into a full electromagnetic simulation. There are many different software packages available to analyse the RCS of objects of various sizes. Here, CST microwave studio (MWS) has been used to simulate the expected RCS of the L and M-Disks. The diameter for the disks was measured, whilst the relative complex permittivity was taken from the generalised relative complex permittivity model discussed in Chapter 4. If the generalised model is to describe the ash correctly, the RCS simulations of the disks along with their measured projected area should show good correlation. The aim here is to demonstrate the validity of the generalised permittivity model in accurately describing the RCS of ash. The effective exposed temperature for the 450 °C disk was used to extract an approximation of its relative complex permittivity due to the remaining carbonaceous material.
Instead of simulating the same waveguide setup, the far-field RCS can be directly extracted, giving an indication of the correlation between the waveguide method to simulated free-space far-field RCS. The simulation parameters used to construct the CST MWS models are presented in Table 19. Only the real part of the relative complex permittivity or what is known as the dielectric constant has only been used. The imaginary component for these low loss materials can be considered to have little effect on the overall backscatter of an object. As the real part of the relative complex permittivity has been shown to be almost linear over frequencies up to 38 GHz, a constant Tanδ model was implemented in simulation. Here the loss tangent is assumed to be zero giving a representation constant permittivity over the X-
Band frequency range. A dispersive model for the ash using Debye type relaxation is only required when the loss of the particle is significant and must be consideration (i.e. $\tan\delta > 0.1$). This is important for analysing dispersed media, such as a group of dispersed ash particles. Again, the RCS has been extracted for the disk at broadside over the same frequency range, where the largest RCS is expected. The simulations were carried out using the transient solver within CST MWS. The results of the simulation for the L and M-Disks are illustrated in Fig. 127 and Fig. 128 respectively. The results of the simulated RCS are in accordance with the measured results for both the L and M-Disks. In both cases, the major variations occur at higher frequencies. This is the result of the mean simulated RCS gradient being larger than that measured at 6.69dB. The difference in the mean gradient is most likely due to interactions between the sample holders and the calibration ball bearings. The calibration factor at each frequency point is responsible for correcting raw $S_{11}$ values and for giving the correct RCS. These interactions are unavoidable, as the rohacell sample holder must be present within the waveguide. The maximum variation in both structures is in the order of 2.5dB. This is reasonable given the low overall reflected power of the disks and the significant influence of the relative complex permittivity on the RCS.

![Graph](image)

Fig. 127 – Simulated RCS of L-Disks of messmate eucalypt ash at various temperatures. Samples of starting diameter $d \sim 7\text{mm}$
The measured and simulated RCS for the disks have shown good correlation at broadside. The investigation of the full mono-static RCS is required, however; this poses a number of challenges when considering the measurements of objects using a waveguide approach [187, 192]. Some limitations can be overcome by using circular dielectric hollow waveguides [188, 189]. This includes the effect of a rotating pin within the board wall of the waveguide and the validity of the calibration once the table has moved to a new angular position. Furthermore, the physical cross-section of waveguides in general limits the possibility of measuring the RCS over a broad frequency range. In this case, the seven millimetre diameter disks can only be physically measured up to 18GHz in a WR-62 waveguide (15.75 mm x 7.87 mm). Increasing in frequency, the disk diameter becomes larger than the cross-section of the waveguide (i.e WR-42 to WR-28). A theoretical and simulated representation of the complete 2D RCS of thin dielectric disks over a wide frequency response (1 – 40 GHz) can now be investigated.

Fig. 128 – Simulated RCS of M-Disk of mesmate eucalypt ash at various temperatures. Samples of starting diameter \(d \sim 4.7\) mm
5.2.1 Wideband Simulated Mono-Static 2D Radar Cross-Section of Dielectric Disks

Extending the broadside RCS measurements and simulations, a complete 2D description of the RCS can be ascertained. Theoretical work on the scattering created from dielectric disks has in recent years become important for remote sensing applications. A primary use of such models has been the investigation of scattering from wet biomass. Here, the relative complex permittivity of living vegetation \((\text{such as leaves})\) has been analysed and applied to thin dielectric disks to numerically model the scattering created from living trees [194-198]. This modelling forms a fundamental part of interpreting SAR image data. Secondary to this modelling of snowflakes which can also be classed as thin dielectric disks. In these cases approximation of the RCS has been made using physical optics (PO) which is a common technique [196]. Other approaches have investigated Rayleigh, Rayleigh-Gans, Kirchhoff, volumetric integral physical optics and volumetric integral equation approximations [194, 195, 197-199]. This work intends to map the extent of the RCS of ash due to its extremely low relative complex permittivity, physical size and required wideband response covered in this dissertation. The analyses of dielectric shapes are important in understanding the scattering created from many natural mediums. Describing the RCS theoretically imposes many challenges, as an electromagnetic wave propagates through the medium. Therefore, a theoretical solution must take into account internal reflections and resonances. Analytical models are limited to short wave/optical or long wave/Rayleigh approximations due to the implementation of a first order Bessel function [198]. All analytical formulations do not accurately take into account edge effects of a disk resulting in a higher error at larger incident angles. They are also not valid for complex shapes. This has been somewhat overcome by the introduction of the numerical volumetric integration equation [199]. In most cases, a method of moments (MoM) or equivalent EM solver offers the best solution for complex structures if computation time and memory is not important [199]. An analysis of the trend in the RCS over a wide frequency band and with respect to changes in their geometric and RF materials properties is desirable. It is important from a scattering perspective, to know the expected RCS over a wide band as the relationship between wavelength and physical size comes into play. In the case of the L-Disk, the diameter is \(0.02 \lambda\) at 1 GHz, \(0.23 \lambda\) at 10 GHz, \(0.7 \lambda\) at 30 GHz and \(0.93 \lambda\) at 40 GHz. The known projected area distributions have further highlighted the diversity in ash particle shapes. Here, the wideband response covers regions where a
Rayleigh approximation is valid at low frequencies and where modified physical optics are valid at higher frequencies. To gain an understanding of how the RCS trends within the L-Disks of the eucalypt biomass when exposed to each temperature range, 2D mono-static RCS simulations were carried out in CST MWS. The 2D mono-static RCS plots over a frequency band of 1 - 40 GHz are illustrated in Fig. 129. The plots have been generated under the conditions of horizontal polarisations (σ_{hh}) by sweeping the incident angle. Coordinate system for the simulation is illustrated in Fig. 124 (c).

There are various important features illustrated in these plots. At low frequencies (typically seen below 10 GHz in those disks exposed to low temperatures), the RCS remains constant with respect the incident angle (θ). This slowly rises at 500 °C to approximately 20 GHz. This band can be modelled effectively using a Rayleigh type scattering approximation however; the accuracy will degrade at higher frequencies due to the flatter RCS response of plate structure. The next area is illustrated between this Rayleigh region and the formation of the first null. Considering the dynamic modes of ash explored within Chapter 3, under the fluttering modes this region begins to affect the maximum scatter contributed by each particle. This is exacerbated when crossing into the first null, seen to occur between 25 GHz and 35 GHz as the exposed temperature increases. In a scenario where vertical pointing radars are observing such particles, the scatter contributed from an individual planar ash particle will increase steadily with frequency under a fluttering dynamic mode. This is to be expected, as the overall scattering amplitude based on the measured standard deviation of the orientation angle of planar ash particles from the horizontal plane (as illustrated in Fig. 72), falls well inside this range.
Fig. 129 – Simulated 2D mono-static RCS ($\sigma_{\text{DL}}$) of the L-Disks of messmate eucalypt ash with the geometric and RF properties outlined in Table 19 with respect to frequency. a) 150 °C, b) 200 °C, c) 250 °C, d) 300 °C, e) 350 °C, f) 400°C, g) 441 °C, and h) 500 °C.
The scattering however, becomes significantly more complex when for example taking measurements with millimetre wave radars that are observing particles at low grazing angles. The scattering is consistently represented here as incoherent scatter. At seven millimetres in diameter, the L-Disk is not an unreasonably sized particle to be present within a smoke plume, however; concentration at this size is expected to be low. The reduction in the permittivity (especially seen between 441 °C and 500 °C), demonstrates its key role in altering the intensity of the scattered field. The retraction of the null at higher effective exposed temperatures is the result of the particle size. A comparison between the CST MWS simulations and the analytical Kirchhoff-type approximation has been made in Appendix A.

To demonstrate that the position of the null is determined by the cross-sectional area of the disks, an analysis of 2D mono-static RCS of four disks ranging in diameter from 1mm, 3mm, 5mm and 7mm is illustrated Fig. 130. Disks were held with a constant effective exposed temperature of 441 °C (\(\varepsilon = 1.15\)) to give an indication of the scatter created from ash found within the exposed temperature distribution outlined from 0.

Fig. 130 – Simulated 2D horizontally polarised mono-static RCS (\(\sigma_{\text{h}}\)) of a messmate eucalypt ash particle with an effective exposed temperature of 441 °C (\(\varepsilon=1.15\)). Particle represented as a disk with various cross-sectional diameters of a) 1mm, b) 3mm, c) 5mm and d) 7mm showing the formation of the first null at higher frequencies.
Fig. 131 – Simulated 2D vertically polarised mono-static RCS ($\sigma_{\text{vv}}$) of a messmate eucalypt ash particle with an effective exposed temperature of 441 °C ($\varepsilon=1.15$). Particle represented as a disk with various cross-sectional diameters of a) 1mm, b) 3mm, c) 5mm and d) 7mm showing the formation of the first null at higher frequencies.

The frequency location of the null at 90° incident angle has been analysed with respect to the ratio between diameter by wavelength ($D/\lambda$) and circumference by wavelength ($C/\lambda = \pi D/\lambda$) of the disks. The circumference by wavelength is commonly simplified to incorporate the wave number (i.e $k = 2\pi/\lambda$, $r=a$, $\therefore C/\lambda = \pi D/\lambda = ka$). Table 20 provides a full analysis of the null location frequency at 90° incidence and its equivalent $D/\lambda$ and $C/\lambda$ ratio. As demonstrated, the null location is matched to the physical size of the scattering disks. It is expected that the null will first become apparent at 40 GHz, when an ash particle has an equivalent diameter of approximately 4.54 mm. The interaction of the null in the dispersed reflective medium must be considered when particles of these diameters are present within a volumetric cell. Observation made at lower wavelengths and elevation angles for example will receive lower scattering from these sized particles. What effects this has on the overall scatter received from dynamically moving planar particles must be considered.
Table 20 – 90° Null Locations with Respect to $d/\lambda$ and $C/\lambda$ ratio

<table>
<thead>
<tr>
<th>Temp. °C</th>
<th>$f_{null}$ (GHz)</th>
<th>$\lambda$ (mm)</th>
<th>D (mm)</th>
<th>$D/\lambda$</th>
<th>$C/\lambda \sim ka$</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>25.78</td>
<td>11.64</td>
<td>7</td>
<td>1.66</td>
<td>1.89</td>
</tr>
<tr>
<td>150</td>
<td>25.78</td>
<td>11.64</td>
<td>7</td>
<td>1.66</td>
<td>1.88</td>
</tr>
<tr>
<td>200</td>
<td>26.055</td>
<td>11.51</td>
<td>6.9</td>
<td>1.67</td>
<td>1.90</td>
</tr>
<tr>
<td>250</td>
<td>27.018</td>
<td>11.10</td>
<td>6.7</td>
<td>1.66</td>
<td>1.90</td>
</tr>
<tr>
<td>300</td>
<td>27.018</td>
<td>11.10</td>
<td>6.7</td>
<td>1.66</td>
<td>1.91</td>
</tr>
<tr>
<td>350</td>
<td>28.119</td>
<td>10.67</td>
<td>6.5</td>
<td>1.64</td>
<td>1.92</td>
</tr>
<tr>
<td>400</td>
<td>28.67</td>
<td>10.46</td>
<td>6.4</td>
<td>1.63</td>
<td>1.91</td>
</tr>
<tr>
<td>441</td>
<td>31.927</td>
<td>9.34</td>
<td>5.7</td>
<td>1.65</td>
<td>1.92</td>
</tr>
<tr>
<td>500</td>
<td>32.8</td>
<td>9.15</td>
<td>5.6</td>
<td>1.63</td>
<td>1.89</td>
</tr>
<tr>
<td>441</td>
<td>36.055</td>
<td>8.32</td>
<td>5</td>
<td>1.66</td>
<td>1.89</td>
</tr>
<tr>
<td>441</td>
<td>26.06</td>
<td>11.51</td>
<td>7</td>
<td>1.64</td>
<td>1.91</td>
</tr>
</tbody>
</table>

5.2.2 Wideband Simulated Mono-Static 2D Radar Cross-Section of an Arbitrary Shaped Dielectric Planar Ash Particles

The scattering response of the circular disks has shown good agreement between measurement, simulation and theoretical (see Appendix A) approximations. The next step in this process is to investigate both the scattering created from an arbitrarily shaped planar particle and the effects of multi-dielectric regions. The effects of these planar particles on the RCS are mostly related to their resultant reflectivity at higher frequencies. At broadside, it is expected that the RCS will show a similar pattern to that of an equivalent elliptical disk. This however, will change slightly at larger incident angles. Finally, the effect of multi-dielectric regions needs to be investigated to provide an insight into how inhomogeneities influence the scattering of fire-generated ash particles. These multi-dielectric regions form when a particle is exposed to uneven heating over its volume. This will be discussed further in section 5.2.3. Transitioning from the RCS of a particle to analysing the reflectivity of many particles, it is important to understand whether ash can be modelled as a homogeneous structure. This plays a strong hand in simplifying the scattering problem and also provides an investigation into the validity of the assumption that the inhomogeneities can be predicted using the average RGB or LAB colour-matching techniques.

Two ash particles of similar size and of different colour have been selected for analysis. Both particles are illustrated in Fig. 132 and despite having distinctly different geometric properties, they only differ in their projected area by approximately 2 mm². The darker, low temperature sample has a lower aspect ratio compared to the high temperature sample. Both
particles show regions of different colours, mostly notable in the lighter colour particle. The effective exposed temperature for both particles has been extracted to be 408.5°C and 489.5°C respectively.

The simulation of the ash particles was achieved by firstly vector tracing their perimeters. This data was then imported and turned into a 3D model within CST MWS. Using the generalised permittivity models outlined in section 0, the 2D RCS has been extracted over 1 – 40 GHz. Due to the asymmetric properties of the particles, both the horizontal and vertical polarised radar cross-sections were extracted. The coordinate system used to extract these values for both particles is illustrated in Fig. 133. As shown, the reflected power is measured in both \( \theta \) and \( \phi \) angles. This gives a 2D representation of the total scattering field expected by the particles.

\[
\text{Eff. Temp} = 489.5 \, ^\circ\text{C}, \, A = 42.63 \, \text{mm}^2
\]

\[
\text{Eff. Temp} = 408.5 \, ^\circ\text{C}, \, A = 44.64 \, \text{mm}^2
\]

\[
\text{Temp } 408.5 \, ^\circ\text{C}, \, A = 44.64 \, \text{mm}^2 \text{ and } b) \, \text{Eff. Temp } 489.5 \, ^\circ\text{C}, \, A = 42.63 \, \text{mm}^2
\]

Fig. 132 – Illustration of the two chosen large ash particle with an approximated effective exposed temperature and projected area of a) Temp = 408.5 °C, \( A = 44.64 \, \text{mm}^2 \) and b) Eff. Temp = 489.5 °C, \( A = 42.63 \, \text{mm}^2 \)

Fig. 133 – Coordinate system used to analyse the 2D RCS of the two arbitrary ash particle
The ash models with their determined permittivity are illustrated in Fig. 134. Here, the particles’ colours represent the mean normalised RGB values extracted for the particles from the image processing method. The resultant 2D dual polarisation RCS simulations for the two particles can be seen in Fig. 135 and Fig. 136.

Fig. 134 – Equivalent colour of the each ash particle. The effective temperature and approximated relative complex permittivity using dE⁰⁰⁰⁰ colour matching for a) Eff. Temp = 408.5 °C εᵣ=1.55 and b) Eff. Temp = 489.5 °C, εᵣ=1.065.

Fig. 135 – Simulated 2D RCS of arbitrary shaped ash particle ‘a’ in: a) phi 0⁰, σ_hh , b) phi 0⁰ σ_vv, c) theta 0⁰ σ_hh, and d) theta 0⁰ σ_vv.
In Fig. 135, the nulls are less formed than those apparent within the disk structures. Looking at the frequency location of the nulls at a theta and phi angle of ±90°, it is shown to be approximately 18 GHz and 30 GHz about theta and 27 GHz about phi. These differences in the null locations are a direct result of the low aspect ratio of the particle (\(AR \approx 0.6\)). The scattering about theta sees a particle with an effective diameter of \(\sim 11.4\) mm, while the scattering about phi sees a particle with an effective diameter of \(\sim 6.8\) mm. Reduction in the null for this example is caused by the complex edge geometry, which increases the effective width of the particles at higher incident angles. These complex edge effects cannot be seen by the analytical approximations. Again, these complex interactions are only predominant at frequencies above X-Band.

In comparison, the high temperature samples shown in Fig. 136 display scattering that is typical of a thin dielectric disk structure. This is because the aspect ratio is close to unison (\(AR \approx 0.95\)). The nulls are well formed. The second null (highlighted in Fig. 136 c  and d)) is caused by the less than unison aspect ratio. The scattering about theta sees a disk of
approximate diameter of 7.0 mm, while the scatter about phi sees an equivalent disk of diameter 8.3 mm.

5.2.3 Wideband Simulated Mono-Static RCS of Multi-Dielectric Planar Ash Particle

To further the analysis, the introduction of multi-dielectric regions has been carried out. Particle ‘a’ has been divided into four regions that were individually colour-processed to determine their approximate effective exposed temperature. The same analysis was carried out for ash particle ‘b’. The relative complex permittivity, along with the effective normalised colour of each region is illustrated in Fig. 137. Table 21 provides a complete breakdown of the material properties calculated for each region labelled in Fig. 137.

![Fig. 137 – Location and equivalent colour of the each ash region. The approximated relative complex permittivity using $\varepsilon''$ colour matching is illustrated in Table 21.](image)

<table>
<thead>
<tr>
<th>Region</th>
<th>L</th>
<th>A</th>
<th>B</th>
<th>Eff. Temp (°C)</th>
<th>$\varepsilon_{\text{eff}}$</th>
<th>Tanδ</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>80</td>
<td>3</td>
<td>-3</td>
<td>430</td>
<td>1.26</td>
<td>0.008</td>
</tr>
<tr>
<td>b</td>
<td>79</td>
<td>6</td>
<td>-4</td>
<td>384.5</td>
<td>1.62</td>
<td>0.020</td>
</tr>
<tr>
<td>c</td>
<td>80</td>
<td>4</td>
<td>-3</td>
<td>425.5</td>
<td>1.30</td>
<td>0.010</td>
</tr>
<tr>
<td>d</td>
<td>79</td>
<td>5</td>
<td>-3</td>
<td>407.5</td>
<td>1.46</td>
<td>0.015</td>
</tr>
<tr>
<td>e</td>
<td>81</td>
<td>1</td>
<td>1</td>
<td>551.25</td>
<td>1.03</td>
<td>0.001</td>
</tr>
<tr>
<td>f</td>
<td>80</td>
<td>1</td>
<td>-1</td>
<td>465</td>
<td>1.06</td>
<td>0.001</td>
</tr>
<tr>
<td>g</td>
<td>80</td>
<td>2</td>
<td>-3</td>
<td>438.5</td>
<td>1.18</td>
<td>0.005</td>
</tr>
<tr>
<td>h</td>
<td>79</td>
<td>5</td>
<td>-4</td>
<td>409</td>
<td>1.41</td>
<td>0.014</td>
</tr>
<tr>
<td>i</td>
<td>79</td>
<td>4</td>
<td>-3</td>
<td>417.5</td>
<td>1.36</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Table 21: Summary of Approximated Relative complex permittivity Within each Particle Region at 10 GHz
The resultant RCS for the multi-dielectric ash particle ‘a’ is seen in Fig. 138. The 2D pattern is very similar to that seen in the single dielectric model illustrated in Fig. 135. A clearer understanding of the differences between the two models has been provided in Fig. 139. Shown here, the introduction of the multi-dielectric model has a similar simulated scattering to an equivalent solid dielectric particle at lower frequencies. The major variations in both theta and phi angles and under both polarisations appear at the formation of the nulls. These variations are expected due to the sharp roll-off of the scattered magnitude at these locations. Overall, the variations do not deviate more than ±6 dB between the two models. The low deviation can be attributed to the similarities in the relative complex permittivity values of each region. The two highest permittivity values found in section ‘b’ and ‘d’ contain the larger surface areas. The smaller areas in sections ‘a’ and ‘c’ do not seem to play a significant role in altering the RCS at broadside. However, edge effects between the dielectric boundaries will again contribute to the large variation in the null regions.

In contrast, the high temperature sample ‘b’ has a number of distinct variations that increase the overall differential RCS to approximately 3 dB. The higher value can be attributed to the relatively large dark region consisting of ‘f’, ‘g’, ‘h’ and ‘i’. There is also a large increase in the RCS at broadside between 17.5 GHz and 32.5 GHz, peaking beyond 6 dB. The nulls are again a source of large error, however; the formation of the second ripple peak is less problematic compared to that demonstrated in ash particle ‘a’. Here, the difference in the models is almost negligible.

Considering the differences from a simulation perspective, the introduction of the multi-dielectric regions does not contribute a significant amount of error in the RCS over many of the incident angles and frequency ranges. Accordance in both cases is shown at frequencies below 10 GHz. At higher frequencies, more complex modelling is required to achieve a better understanding of the scattering phenomena. Here, it has been shown that the location of the null is likely to be the highest source of error. It was shown that the null first appears at 40 GHz, when an ash particle is greater than ~4.54 mm in cross-sectional length. Taking into account the known projected area and aspect ratio distribution measured in 3.6.1 and 3.6.2, particles of higher cross-sectional length become less and less common. Within a pool of potential ash created within a fire, the likely error induced by a single large particle will only become significant at a few incident angles. As ash particles are consistently moving in a dynamic environment the induced error may only be present for a short amount of time.
Fig. 138 – Simulated 2D RCS of arbitrary shaped ash particle ‘a’ with multi-dielectric regions: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{hv}$, c) theta 0° $\sigma_{hh}$, and d) theta 0° $\sigma_{vv}$

Fig. 139 – Difference between solid and multi-dielectric simulated 2D RCS of arbitrary shaped ash particle ‘a’: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{hv}$, c) theta 0° $\sigma_{hh}$, and d) theta 0° $\sigma_{vv}$
Fig. 140 – Simulated 2D RCS of arbitrary shaped ash particle 'b' with multi-dielectric regions: a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{vv}$, c) theta 0° $\sigma_{hh}$ and d) theta 0° $\sigma_{vv}$

Fig. 141 – Difference between solid and multi-dielectric simulated 2D RCS of arbitrary shaped ash particle 'b': a) phi 0°, $\sigma_{hh}$, b) phi 0° $\sigma_{vv}$, c) theta 0° $\sigma_{hh}$ and d) theta 0° $\sigma_{vv}$
As the horizontal orientation distributions of both planar and cylindrical ash particles have been shown to have standard deviations of 31.98 and 35.84 respectively, any modelled reflectivity can only be truly represented statistically. Using a solid dielectric representation of the ash may also provide satisfactory scattering approximation if it is assumed that each particle will have relatively even heating distribution. Even heating is more likely to occur in smaller ash particles due to their relative size. Furthermore, the formation of dielectric regions (i.e. areas of different dielectric constants) is in most accounts only applicable to extremely large particles. These dielectric regions form due to uneven heating of a biomass materials. Illustrated by those examples of particle geometry from six genera in section 3.6.4, multi-dielectric regions are rarely seen.

The error within this scattering assumption will always be skewed towards ash particles with a higher effective exposed temperature. This causes the scattering to be under-predicted at higher frequencies.

Moving towards the modelling of the reflectivity of ash, the simplification of each ash model using an effective solid equivalent will provide a satisfactory outcome. It should also be noted creating and implementing a statistical model which can describe a multi-dielectric ash particle is near impossible in a simulation environment. This is because there are an infinite number of possible combinations of both localised areas and relative complex permittivity values.

The geometry can be further simplified, as the cross-sectional length determined by the aspect ratio and the projected area distributions is all that is required to form a reasonable scattering model. The analysis of the RCS of ash has provided a good characterisation of how ash particles are expected to interact with electric fields. The generalised permittivity model has again shown good correlation with the broadside RCS measured data. Simulated particle analysis has provided an insight into the complex scattered fields expected from planar ash particles. This has provided an in-depth analysis for applying the simulation models and for understanding the reflectivity of multiple ash particles.

The reflectivity outlined in the research roadmap (see section 2.5.2) is the final stage of analysis in this dissertation. The collected statistical data can now be correlated to analyse a first order approximation of the expected reflectivity of a dispersed ash medium.
5.3 Relative Complex Permittivity Distribution of Ash Created from Fires

In Chapter 3, it was shown that there is a large variation in the types of ash particles being produced in open fires. Little correlation was found between the remnant ash particles being produced within a fire and the equivalent flame temperature. To define the total scattering from a dispersed medium such as ash, the contributions of each ash particle must be known. The flame temperature cannot deliver enough detail about ash to provide a sufficient understanding of its total scatter. It then becomes apparent from the definition of the reflectivity that both the geometric properties and relative complex permittivity on a particle-by-particle basis must be known. Mapping of the relative complex permittivity of the ash under controlled temperature conditions only provides knowledge of how biomass acts as a material. Illustrated by the open fire tests in Chapter 3 and the complex permittivity analysis in chapter 4, ash has various RF properties based on their individual exposed temperature. Due to the fluidic nature of fires temperatures of the flaming region vary from area to area with time. Thus, a fire is likely to create a distribution of particle properties with variations in their relative complex permittivity values and hence their scattering properties. This is not so apparent in traditional precipitation reflectivity modelling.

Further adding to the complexity of the reflectivity of ash is a unique case where each particle may possess different relative complex permittivity regions. This is to say that an ash particle created from a fire in uncontrolled conditions is inhomogeneous in nature. Furthermore, due to the way cell structures in all plant and tree species are arranged in the thickness plane, it is likely that the material will also be slightly anisotropic in nature. To investigate this anisotropic property is extremely difficult due to the small, cross-sectional thicknesses present within biomass. Ideally, the same sample should be measured in both directions to identify the anisotropic behaviour. In reality, this can only be achieved using a micrometre-sized coaxial transmission/reflection method. The relative complex permittivity of the material along the area plane may however, be extracted using a microstrip transmission/reflection method. Here, the biomass is laid on top of a microstrip and calibrated using a TRL calibration. As the biomass changes the impedance of the microstrip, the permittivity can be extracted [139]. This however, has not been carried out within this
dissertation, as it would require a vast number of measurements to statistically prove any anisotropic behaviour.

A high-resolution image of ash created from messmate eucalypt biomass exposed to temperatures above its ember point is illustrated in Fig. 142 and demonstrates this inhomogeneity. Inconsistencies are evident in the colour of the ash, from light greys to blacks. Here, the black regions represent areas of the ash with higher carbon content and so have been effectively exposed to lower temperatures. These darker regions will have different relative complex permittivity values to those within the lighter grey areas.

![Image of ash](image)

*Fig. 142 – Example of ash created from biomass exposed to temperatures above the ember point of the messmate eucalypt biomass >450 °C.*

As the effective relative complex permittivity of the biomass has been successfully measured in chapter 4, certain assumptions about the material can be made to simplify the scattering problem.

If an ash particle is ejected into the atmosphere and can be characterised as having only small inhomogeneities, a simplified model can be produced to describe the effective relative complex permittivity of each particle. In the case of the larger ash particles produced within the burn chamber, large areas of inhomogeneities are rarely observed *(see section 3.6.2).* Furthermore, demonstrated by the measured relative complex permittivity and generalised permittivity model, the expected shift in the real part of the relative complex permittivity is not significantly large. Here, it has been predicted that the biomass, which falls within the effective exposed temperature ranges above 400 °C, will shift by only \( \varepsilon = 0.5 \). At low
concentrations of particles within a finite volume, this will have little if any effect on the overall scatter. This becomes apparent when considering that the relative complex permittivity will naturally deviate around the median values used to describe the generalised permittivity model, which is a result of the inhomogeneities of the cell structures. An analysis of the radar cross-section of ash assumed to have a constant effective permittivity and multi-dielectric regions will be fundamentally explored in section 5.2.

The question then arises of how one may determine a probability distribution function for the particle being produced within fire. Looking at traditional precipitation measurements, rain can be characterised simply by assuming that the permittivity of each raindrop remains the same under constant temperature and pressure. For ash particles ejected into the atmosphere, this is not the case. Considering the normalised mass loss curves measured in section 3.7.1, the biomass (in the case of the eucalypt and acacia genera) will only effectively burn until all of its volatile compounds have been expelled. In the case of low intensity fires, the median particle temperature will fall somewhere below 450 °C, while a high intensity fire may shift the median value above 450 °C. This is however, a simplified realisation of the expected distribution of ash particles produced within fires. A more in-depth investigation is required, as it does not take into account what effects the thermodynamic cycle has on carrying unburnt or partially burnt structures into the atmosphere. These unburnt or partially burnt structures have been well documented and are the primary cause of spotting fires.

As demonstrated within chapter 4, the effective exposed temperature distribution of ash particles can provide a direct correlation to their effective relative complex permittivity. It has also been shown that the colour of ash provides a direct correlation to its exposed temperature. This has typically been used to correlate the severity of fires to soil conditions, such as [78, 110, 112, 200]. If it is assumed that the average colour of each ash particle represents the average exposed temperature, an effective relative complex permittivity distribution can be extracted using the image processing method outlined in Appendix C. To achieve this, colour-matching techniques can be implemented where the average pixel value of each ash particle can be matched to a predefined colour model. These colour models for all genera explored within this dissertation can be observed in Appendix D.

Two colour space models were defined for messmate eucalypt and used as part of the matching method. These were in RGB and CIELAB colour spaces. The matching models were created by mapping the RGB and LAB colours of the biomass at the designated exposed temperature ranges up to 600 °C. Ash samples were obtained by collecting ground litter and
placing it within the linear burn chamber. A number of samples were prepared and burnt under similar conditions (800 °C - 900 °C flame temp), where the flying ash collected on the mesh screens were scanned at high resolution and processed using the image processing technique. More than four thousand ash particles were collected and scanned to form part of the analysis. These were the same particles used to create the statistical distributions in Chapter 3.

Four common colour-matching techniques (two for RGB colour space and two for LAB colour space) were explored [201-204]. The best RGB colour space-matching technique was found to be that which was based on an intensity Euclidean vector system (\(\Delta I_{r,g,b}\)) (see Eqn. (32) showing the lowest error distribution.

\[
\Delta I_{r,g,b} = \sqrt{\Delta I_r^2 + \Delta I_g^2 + \Delta I_b^2}
\]  

(32)

The best LAB-based colour matching method was founded on the CIEDE2000 algorithm (\(\Delta E^*_{00}\)) [203]. Investigating the distribution using two colour spaces offers the advantage of independent validation of the PDF. If the PDFs in both colour spaces show similar distributions, confidence may be afforded in the colour-matching technique. The exposed temperature distributions for the best RGB and LAB matching methods are illustrated in Fig. 143 and Fig. 144 respectively.
Fig. 143 – Effective exposed temperature probability distribution for the given $\Delta I_{rgb}$ matching method with respect to the normalized RGB colour model of the messmate eucalyptus tree.

The exposed temperature distributions for both colour spaces show very similar results, thus indicating good matching correlation between the ash particles and the measured colour models. Illustrated from these PDFs is the formation of a large distribution of particles with an expected exposed temperature within the range of 400 °C – 450 °C.

The RGB distribution shows a slight spreading within this range, causing a lower frequency count compared to the LAB distribution. Slight differences can be seen in the second distribution peak between 225 °C and 275 °C. Here, the LAB distribution shows a smaller overall frequency within this range and a third, smaller peak between 160 °C – 190 °C. Both these peaks represent particles that are partially burnt and still contain a large amount of combustible volatiles. Though these particles form in the cooler regions of a fire, they are still carried away from the main fire front based on the localised air velocity and direction. The exact reason for this requires further exploration as to determine the types of particles forming at these lower effective temperatures.
The variations between the RGB and LAB matching techniques within this range are due to the significantly different contour shapes of each respective colour channel. The CIEDE2000 matching technique provides a number of advantages over the $\Delta l_{rgb}$ method, the most significant of which is the introduction of an extra dimensional parameter linking the Chroma and Hue. The error distribution for each matching technique is illustrated in Fig. 145. The matching error is shown to be quite reasonable for both cases, with the collected ash particles complying with the colour models to within 5%. The CIEDE2000 matching technique by definition will provide the best approximation for the exposed temperature PDF. This is however, not illustrated by the error distribution as shown in Fig. 145.
Chapter 5 – Radar Cross-Section and Simulation

Fig. 145 – Box-plot of the error distribution for the two best colour matching methods used to approximate the exposed temperature PDF’s.

The higher errors associated with the CIEDE2000 are a result of this extra dimensional parameter, which compounds the matching error. After extensive testing, the CIEDE2000 matching method has been shown to give exceptional matching performance over a wider range of variable colour inputs [203].

The PDF’s realistic results, especially with the median of the main distribution falling close to the 450 °C point. To find relative effective relative complex permittivity of the distribution, one can simply substitute the generalised effective permittivity model illustrated in Fig. 116 and Fig. 117 for the $\Delta E^{*00}$ effective exposed temperature distribution.

5.3.1 Coupling between Particle Projected Area and Effective Exposed Temperature.

To further analyse the temperature distribution and understand what effects this may or may not have on the geometric properties of ash particles, a statistical correlation can now be investigated. This correlation is required to provide information on whether there is any unexpected skew in the area or aspect ratio distributions with respect to ash particles forming at specific exposed temperature ranges. For example, if larger particles are forming at lower effective exposed temperatures, this indicates that the biomass was not burnt efficiently within the burn chamber. Alternatively, if smaller particles make up this majority at lower temperatures this may be an indication that these smaller particles are forming in the core of larger biomass structures. When disturbed by updrafts caused by the thermodynamic cycles, these carbonaceous regions may break away forming ash particles with higher carbon content and thus permittivity. Furthermore, if smaller regions are formed in low, localised oxygen conditions, the biomass may also undergo a partial form of pyrolysis where the structure will remain relatively stable at elevated temperatures. Two examples of the formation of these small carbonaceous regions in eucalypt ash have been illustrated in Fig. 146. As depicted, these regions are surrounded by areas that have burnt at much higher temperatures and consequently have a more fragile structure.

Taking the exposed temperature distribution (from section 0) along with the respective information about each particles projected area and aspect ratio (as measured in chapter 3), a
3D distribution can be achieved. This will provide further insight into the causes of the lower exposed temperature distributions noted in both Fig. 143 and Fig. 144 respectively. As the CIEDE2000 method is proven and has been shown to have good error performance [203], it will be used to calculate the temperature distributions in this section. The 3D distribution of exposed temperature, area and frequency is illustrated in Fig. 147. Furthermore, the AR of the same distribution is given in Fig. 148.

Fig. 146 – Examples of the formation of ash from eucalypt leaf structures in a) poor combustion conditions, b) good combustion conditions. Red circles represent the formation of small carbonaceous regions contributing to the lower exposed temperature distributions
Fig. 147 – A 3D representation of the temperature profile for the particle populations with respect to their projected surface area. Colour bar represents frequency of particles.

Fig. 148 – A 3D representation of the temperature profile for the particle populations with respect to their aspect ratio. Colour bar represents frequency of particles.
Illustrated by both the projected area and aspect ratio distributions with respect to the effective exposed temperature is a constant representation of the respective distributions formed in Chapter 3. The projected areas of ash particles that form at lower temperatures are shown to display a generalised pareto-type distribution. This supports the argument that these particles are primarily small and could be forming in larger biomass structures. Similarly, the overall shape of the particles with regards to aspect ratio is again centred on the same median value. At these lower effective exposed temperature ranges, both distributions have less spread due to the lower particle count. The main distribution focused between 400°C-450°C shows identical properties to those outlined in Chapter 3. The distribution also illustrates that a number of larger particles are present within the samples (Area >1mm²). At high microwave and millimetre waves this will contribute significantly to the scattering of a plume.
5.4 Ash Reflectivity

The analysis of the reflectivity of ash is the final area of investigation for this dissertation. The reflectivity as demonstrated in the research roadmap (see section 2.5.2) provides an indication of the total scatter given from a number of dispersed ash particles within a known volume. Generally, the reflectivity is extracted from this total scatter and normalised to a predefined unit volume (i.e. cm³, m³, etc.).

The complex nature of fires results in a large number of possible scattering scenarios. To focus the analysis of this section, only a single scattering scenario will be considered. From the knowledge gained within the previous chapters, a good representation of the reflectivity of ash produced from a moderate temperature fire can be achieved. Other scenarios require further investigation to build a complete scattering framework for ash. These include the effects of other scattering sources such as Bragg/clear air scattering, condensation and ionisation. Furthermore, a consideration for the possible inclusion of coherent particle scatter must be made [65, 66].

The analysis of the reflectivity when isolated to the contributions of ash particles cannot be conducted by observing the scattering of fires using radar. Here, the total contribution of all scattering sources becomes the principle analysis. EM simulations provide the best solution for analysing the contributions of the ash particles in the total scatter seen by radar. This holds particular importance when observing small fires in their early stages of propagation. The influences of the other scattering sources are localised to small flaming. In practical applications, radars observing the presence of small fires will do so at low grazing angles above the ground.

Before electromagnetic simulations can be carried out, the performance of the EM scattering regime needs to be validated. The mono-static RCS is shown to be in accordance with ash particles of defined geometry. This can be expanded to investigate the contributions of many scattering targets within a volume of space. Measuring the scattering from multiple ash sources imposes a number of challenges, including the variability and sensitivity requirements of such measurement system. Furthermore, multiple ash particles cannot be measured using a static-type arrangement. Here, dynamic RCS measurements must be made and along with this, a number of assumptions must be imposed.
5.4.1 Measurements of Reflectivity of Eucalypt Disks

Dynamic measurements have long been associated with moving objects [205]. The development of dynamic RCS measurements imposes challenges such as correlating particle scatter to concentration, Doppler effects and the dynamic behaviours of the particles within a viewing area.

It is known form the analysis of the static RCS of disks that the overall reflectivity of dry biomass is low. This requires a highly sensitive measurement system to achieve a detectable signal. The outlay of the dynamic measurement setup in this case must be constructed inside a millimeter wave anechoic chamber to allow for higher sensitivity to the particle scatter. This effectively guarantees a drop in the noise floor. The dynamic component of the RCS setup arises from the ability to disperse targets within a known volume. This can be done by taking advantage of the ascent and descent characteristics of the ash particles. Both represent the different behaviours of ash particles typically found within smoke plumes. In a practical sense, this can be achieved by either dropping particles or by blowing them upwards through an illuminated area.

To keep the particle within a predefined volume, the descent phase provides the best solution. The particles in this case fall due to gravity with a coupling to the fluidic interactions provided by the surrounding air. The dynamic scattering of ash particles under the descent phase is most likely seen by radar systems observing smoke plumes at distances away from the main fire front. This provides a realistic representation of the reflectivity, which can be ascertained in a physical measurement system for confirming the agreement in reflectivity to simulated data.

Looking at the known RCS of disks made from ash, it is again unlikely that the use of low power lab equipment will provide enough signal-to-noise ratios to observe any significant scatter. For this reason, Ka-Band was chosen for this measurement setup to help make the measurement more sensitive, based on the hardware available.

A 3D illustration of the bi-static dynamic RCS measurement setup can be seen in Fig. 149. The setup consists of four elements: the measurement rig, RF components, motion control and a high speed video camera. The measurement rig is an open-sided box that contains a paper conveyor belt used to carry the scattering medium. All components are made from dielectric material to reduce the possibility of resonant and highly reflective structures. The RF components consist of two QuinStar Q-Band (33 - 50 GHz) standard gain horns. The typical mid-band gain is 24 dB, with a 3 dB beam width of 12 degs. The bi-static angle
between the horns and the focal point was measured to be approximately 7.5°. 3dB scattering volume was further estimated to be 10 mm radius by 45 mm, based on observations of the dynamic behaviour of the particles.

The center frequency was originally chosen to be approximately 38 GHz to coincide with the permittivity measurements carried out in chapter 4. During the testing phase of the systems an operating frequency of 37.4 GHz was finally chosen due to the location of a null in its response. This provided an extra few dB in sensitivity for the measurement.

The range to satisfy the far-field requirement as described in Eqn. (30) for the setup is approximately ~ 0.8 m. The total range length of the measurement structure was designed to be 1.0 m. Line of sight surfaces were also lined with RF absorber material to minimize reflections. The RCS setup utilized a signal generator and spectrum analyzer instead of a VNA to improve the dynamic range and further increase sensitivity.

The motion control consisted of an Arcus Technologies PMX stepper controller and a NEMA 17 stepper motor. These were all programmed through MATLAB along with GPIB control over the signal generator and spectrum analyser. Finally, a high-speed 240 fps video camera was placed inside the chamber to observe the falling particles. The video data was synced to the measured reflectivity and then image processed frame by frame. The intent here was to correlate the number of falling particles present within the scattering volume to the measured reflectivity.

It has been shown that the relative complex permittivity of the ash follows a predefined trend. The measurement of the reflectivity in this case has been designed to ascertain the validity of simulated data. To do so, a number of controls were imposed on the measurement domain. Using ash collected from open fires or a burn chamber for example, allows for too many unknown variables. As the RCS of a particle relates largely to its geometric shape and RF material properties, controlling these parameters is essential. In a similar fashion to the controlled ash particles analysed for their mono-static RCS, disk structure limits these complexities.
Fig. 149 – 3D illustration of the dynamic RCS measurements system housed inside RMIT’s millimetre wave anechoic chamber. Biomass samples are heaped onto a paper conveyor belt which is driven by a high precision Arcus Technologies NEMA 17 PC programmable stepper motor. The stepper is shielded using absorber foam.
Although ash samples are ideal for measuring the reflectivity, they cannot be realistically implemented into such a measurement system. This is primarily due to their fragility which causes them to easily break-up. This has been found to be a frequent problem when handling them and less of an issue when they are suspended within the atmosphere do the larger external forces applied on their surface. For this reason it is difficult to control the geometric shape of the particles and thus directly compare their scattering response. Using un-burnt biomass, although not ideal, provides a viable alternative means for analysing the reflectivity.

The un-burnt biomass samples also provide a consistent permittivity reference without the need to expose the disks to heat, which introduces further unknowns. The biomass samples were prepared by stamping hundreds of small disk structures out of leaves. The median dried diameter of the disks was measured to be approximately 6.1 mm. A complete overview of the preparation and placement of the disk structures on the paper conveyer can be seen in Fig. 150. A large number of disks were heaped into rows, evenly spaced out along the conveyer. This was used as a check between measurements to see if the stepper motor caused any unforeseen interference. No significant magnitude displacement was observable, however; very small periodic phase oscillations were noted due to the movement of the belt and not the motor.

Fig. 150 – Illustration of sample preparations and image of falling particles used in the dynamic RCS measurement system. Samples stamped from Eucalypt biomass then dried. Samples then placed on paper conveyer where a stepper motor drives them over edge.
The setup was calibrated using standard shapes of known RCS. These shapes comprised of three aluminum disks of diameters 20 mm, 30 mm and 100 mm, which were aligned and measured with the setup.

The mean difference between the known RCS of the disks to the corresponding received power was -39.36 dB ±0.35 dB. The corresponding measured noise floor represented a minimum sensitivity of ~-37.65 dBsm ±0.35 dBsm, or that equivalent to a thin aluminum disk measured at broadside of 6.55 mm approximate diameter. A Ka-band pre-amp was also included on the transmit end. The maximum transmit power at horns was measured to be 11.96 dBm.

The measurement procedure began by initiating the signal generator that conducted a measurement sweep of 601 data points. Following this was the initiation of the stepper motor. The measured data consisted of five noise measurements that included the movement of the stepper and paper conveyer. After the block of five noise measurements, the scattering biomass samples were tested (i.e 5 x noise, 1 x sample. 5 x noise, etc.). The spectrum analyser was then instructed to begin recording zero span data at 37.4 GHz. In these measurements, the effects of Doppler shift can be neglected as the particles fall perpendicular to the propagating incident field. Taking the measured RCS data, the reflectivity can be calculated based on the known scattering volume. In this case, it has been determined to be approximately 100 mm x 100 mm x 40 mm at the crossing of the beam. The 100 mm length and width representing the projected area towards the horns was guided by the paper conveyer and knowledge of the beam width. The 40 mm depth dimension was determined by measurements. A sample of the equivalent processed reflectivity data of four sample measurements is illustrated in Fig. 151. Processing of the return signal included an integration filter and a clipping of the returns lower than $\eta=-3.7 \text{ dBm}^2\text{m}^{-3}$. The relatively fast sampling rate of the spectrum analyser (500 Hz) resulted in a ‘snapshot’ measurement of the eucalypt disks transitioning through the illuminating volume. Furthermore, this snapshot view can be assumed due to the slow transitioning falling speed of ash explored in section 3.8.2.

As illustrated, the response of the eucalypt disks is only just above the noise floor, however; reflections are distinguishable at each of the biomass sample numbers (i.e. 6, 12, 18, and 24). Taking advantage of the high-speed video data, a correlation can be made between the detected scatter and the number of particles present within the scattering volume.
This knowledge can be expanded to take into account the expected simulated reflectivity for the particles and thus, an inverse scattering model can be achieved. In this case, it is highly favourable to examine the relationship between reflectivity and particle concentration/bulk density.

The relationship becomes important when attempting to estimate the amount of biomass consumed within a fire in near real-time. This can then be expanded with the aid of known regional vegetation models for example, to estimate the size and intensity of fires. To correlate the reflectivity to the number of particles and thus the concentration/density of biomass present per unit volume, the high-speed video data was image processed. The time axis shown in Fig. 151 was synchronised with the high-speed video data. Where clear scattering was observable from the biomass disks, the resultant reflectivity was extracted. The resultant video frames were then isolated and the number of disks present within the frame were counted. The concentration was then approximated by multiplying the mean bulk density of the disks by their mean volume. To investigate and confirm the observable scatter, a replica scattering model was created within CST MWS. The scattering model was created by means of a custom random particle generator, using a VBA macro. The geometry was set

---

**Fig. 151 –** Filtered reflectivity ($\eta$) for dried messmate eucalypt disks. Red arrows provided on sampling range to indicate location of biomass measurements (i.e. 6, 12, 18 and 24). All other samples are background noise with the inclusion of the stepper motor and paper conveyer movements. Atm. Temp. 23 °C, RHI 36%
using disks with a standard diameter of 6.1 mm. The thickness was varied based on the normal distribution measured for the messmate eucalypt leaves given in section 3.6.3. The disks were then generated and translated randomly within the pre-defined scatter volume by their six degrees of freedom (*i.e. 3 translations and 3 rotations*). The concentration was extracted by storing the geometric data about each disk. The volume was then calculated for the disks and the mean measured bulk density was used to calculate the concentration. The particles were randomly orientated as they were dropped off the paper conveyor in a vertical orientation. As the particles are expected to fall under the fluttering or tumbling dynamic modes, the transition from the vertical state to horizontal state is expected to act more like a randomly dispersed medium. The comparison between simulated reflectivity and measurement data points are shown Fig. 152.

![Box-plot of measured vs. simulated reflectivity for controlled eucalypt leaf particles based on measured relative complex permittivity and known geometry at 37.4 GHz. Measured data used to confirm the expected simulation scattering responses above the measurement noise floor (NF). Atm. Temp. 23 °C, RH 36%](image)

At each simulated concentration interval a number of different models containing the same particles in different random positions and orientations were analyzed (*more than 20 simulations per concentration*). As the same number of particles will never respond identically from one model to the next (*i.e. due to changes in their position and orientation*), it is important to consider the variance or statistical distribution of the scatter when
comparing simulations to measured results. For example, the simulated data at a concentration of \(\sim 25 \text{ g/m}^3\) shows quite a large variance in the expected scattering field. Here, the same number of particles within the same simulated scattering volumes can be expected to return a reflectivity from \(-5 \text{ dBm}^2\cdot\text{m}^{-3}\) to \(-24 \text{ dBm}^2\cdot\text{m}^{-3}\). As the highest reflectivity here is \(-5 \text{ dBm}^2\cdot\text{m}^{-3}\) and the given noise floor is \(-4.24\pm0.35 \text{ dBm}^2\cdot\text{m}^{-3}\) no scatter should be observed from this concentration level. This is seen to be the case in Fig. 152. On the other hand at a concentration of \(\sim 140 \text{ g/m}^3\) the variance of the scattering field is expected to fall between \(\sim 1 \text{ dBm}^2/\text{dBm}^{-3}\) to \(-14.5 \text{ dBm}^2\cdot\text{m}^{-3}\). In this case the upper end of the simulated deviation has a higher probability of being detectable at the receiving antenna of the setup. This does not mean that dropping particle with a combined concentration of \(\sim 140 \text{ g/m}^3\) will always be visible.

Scatter above the minimum detectable reflectivity of \(\eta_{vv} = -4.24\pm0.35 \text{ dBm}^2\cdot\text{m}^{-3}\) is shown to be in accordance with the statistical variance seen in the simulated results. The rise and fall seen in the simulated data is a consequence of the bi-static antenna arrangement. This rise and fall is a consequence of changes to the reflected scattered far-field radiation pattern of the particles. As the number of particles increases within a volume, the scattered field will increase in intensity. A consequence of this increase in the field intensity is an increase in the directionality of the reflected field. This effect is similar to that seen when measuring the RCS of a plate while increasing its cross-sectional area. In the case of ash, however: the scattering is purely incoherent. In this case due to the bi-static arrangements the first scattering null begins to influence the received power at a particular particle concentration level. Here, this is seen to occurs somewhere around a particle concentration of \(\sim 140 \text{ g/m}^3\). After this concentration level the variance of the received power is seen to drop due to the interacting null. With consideration given to the variance of the scattering data, the measured data is seen to be detectable above the noise floor in its expected range. This gives some confidence in the correlation between measured and simulated data under dynamic conditions. To confirm the lower portion of the simulated scattering variance which falls below the noise floor, the measurement setup requires higher gain antennas and high power amplifiers. This however, can also be solved by using a mono-static measurement system which was not achievable here. In the case where a mono-static arrangement is used the received power will continue to increase with particle concentration [63].
5.5 Reflectivity Simulations

The statistical distributions measured for the messmate eucalypt ash provide sufficient information to simulate their radar reflectivity. It should be noted that without extensive radar measurements to quantify the concentration of particles to reflectivity, a full understanding of the scattering field cannot be obtained. This said, even correlating the particle concentration to measurements of scattering using radar introduces its own complexities. It has been shown that ash contains many different geometrical shapes, has changing relative complex permittivity with effective exposed temperature and will display up to three different dynamic modes. For large crowning fires for example, it is common for spotting fires to be started hundreds of metres ahead of the main fire front. These are caused by large pieces of burning debris (such a bark) being displaced by the huge thermal updrafts. These events although rare, are not impossible and are difficult to account for in both modelling and measurements.

As the scope of particle scatter is wide, accommodating every aspect of such complex phenomena cannot be achieved. To limit the scope within this section, only particles created from moderate temperature fires will be discussed. This will further be limited to the eucalypt ash created from leaves. It should be noted that the statistical distribution measured about ash will not change with the exception of the effective exposed temperature distribution explored in section 0.

Using the generalised permittivity model, good agreement has been made in describing the individual radar cross-sections of ash particles using CST MWS. Applying this to studying the reflectivity of un-burnt biomass disks in the previous section, accordance between measured and simulated data has been demonstrated.

This section will discuss the formation of a complex simulation framework using both CST MWS and MATLAB. It will then analyse the results of the simulated reflectivity under a number of different states. Investigations into the reflectivity under two of the dynamic particle modes have been considered. The first is the fluttering mode seen during the descent phase, and the second is the chaotic or random mode seen during the ascent phase. The effects of polarisation and incident angle on the total scattered field have also been considered.
### 5.5.1 Simulation Framework

Modelling of the reflectivity of dispersed mediums in recent years has shifted towards using a full EM solution due to the wide spread success of commercial EM codes. Traditionally, theoretical modelling of the reflectivity is limited to numerical or analytical approximations. These approximations assume a constant effective permittivity for each particle and a generalised geometric model is almost always implemented to simplify the scattering problem. These models are also generally limited to the Rayleigh region, which restricts their domain to frequencies below X-Band in most general cases. As the theme of the dissertation has been to investigate the properties of ash into Ka-Band, these models cannot be implemented as a means for accurately describing the expected reflectivity over wide bands.

As shown by the RCS modelling of an individual ash particle, the formation of nulls of randomly shaped particles differs from that of disks. This is the result of edge effects, which are not taken into consideration. This becomes critical when trying to describe ash under its three dynamic modes. Here, in the case of planar particles that display the fluttering mode, radars observing these particles at low grazing angles will see dominant scatter from edge effects. The contribution of these edge effects has been shown to become significant when moving towards millimetre wave bands.

As CST MWS has shown promising results in describing the scattering of the ash, it will be used here to simulate its reflectivity. Aiding in the development of a simulation framework is CST MWS controllability over an OLE (Object Linking and Embedding) server using visual basic (VB) commands. This allows for CST MWS to be driven externally through its extensive VB libraries using other programming languages. Here, MATLAB has been chosen as the primary programming environment to control CST MWS. The rationale behind using MATLAB comes about from its powerful statistical libraries, which are far superior to the native VB language in CST MWS.

Presented in Fig. 153 is a simplified block diagram for the MATLAB - CST-MWS simulation framework. The first requirement for the simulation framework is the user input limits. This includes the statistical probability distribution functions, imposed limits to the geometrical size of the particle, scatter volume, dynamic modes and frequency ranges. The simulation routine begins by an OLE handshake to initiate control. MATLAB begins a new CST MWS session which sets up the simulation environment (i.e. simulation frequency range,
units, background medium, scatter volume and boundary conditions). The next routine generates a single particle using the statistical PDF’s. This is defined by generating a random three to ten point normalised polygon curve representation of a particle. This particle is then stretched, based on the required aspect ratio PDF. Following this, the particle is then scaled to meet the required area PDF value. Both the aspect ratio and area PDF are generated using a skewed random number generator within MATLAB. The curve representing a 2D ash particle is then extruded into the third dimension using the thickness PDF. Finally, the particle is designated an effective temperature determined by the effective temperature distribution outlined in section 0. This is then used to designate the effective permittivity of the particle based on the generalised permittivity models described in section 0.

Before this information is supplied to CST MWS to build the particle, the scatter volume is defined by a cube assigned the properties of lossless air \((i.e \ varepsilon = 1.00059 + i0)\). This is only carried out on the first iteration. The particle is generated, translated, rotated and inserted within the defined scatter volume. The translation and rotation defining the six degrees of freedom for the particle are used to describe their dynamic modes. Here, the translation and rotation are both generated randomly for the ascent phase or in the case of the tumbling and fluttering modes, in the descent phase using a skewed normal PDF based on the measured orientation angle in section 3.8.2.

The generated information about the ash particle is then exported from MATLAB to an excel spread sheet. This provides a full record of the particle’s geometry, position within the scattering volume, RF and physical material properties \((i.e. \ v, m, \ eT, \ etc)\).

The simulation has two options, which include a bulk S-Parameter simulation that can be used to determine the effective relative complex permittivity of the scattering volume. Also included is a plane wave simulation used extensively for the extraction of scattering information. The plane wave is used to simulate both horizontal and vertical polarisations, as well as different incident angles. Cross-polarisation information is also extracted from the plane wave simulations.

To simulate the scattering over a wide range of frequencies, only the transient solver can be used effectively within CST MWS. This is because a frequency domain solution is computationally expensive for these dispersed models.
Fig. 153 – Simulation framework showing the major components of the CST MWS/MATLAB co-simulations scheme for analysing the reflectivity of ash particles.
As the planar structures are non-resonating with low dielectric values, the transient solver in CST MWS is well suited. Once the particle’s information has been stored, CST MWS is then set up to solve in it transient solver. Meshing is defined for the highest frequency, with mesh enhancements made for a hexahedral mesh.

Typical mesh cells range from eight to sixty million, depending on the number of particles within the pre-defined scattering volume. Here, this was chosen to be a 45mm x 45mm x 45mm cube. Simulation time for an iteration loop of one to twenty-five particles takes in the order of one week to complete. This approximately generates one Giga-byte of scattering information under both polarisation and three incident angle schemes from 1 - 40 GHz. The scattering data is extracted at the completion of each simulation sub-loop using an ASCII format and is post processed using MATLAB. The simulations were carried out on two PCs using CST Studio 2012 SP08. The first machine is a HP Z800 with dual Intel Xeon processors, 64GB of RAM and 15,000rpm HDDs. The second machine is a custom-built Intel Core i7-2600k processor, 16GB RAM and SSD HDD’s.

![Fig. 154 – Illustration of the simulation planes (top left to right 90° to 0° elevation angles) and geometric modelled ash particles (bottom) used within the CST MWS simulations. A total of 30 ash particle present within this illustrated model, representing a maximum concentration of 26.59 g/m²](image-url)
At the completion of the simulation, the total RCS was extracted from CST-MWS. These results were then taken and divided by the pre-determined scattering volume to determine the reflectivity factor as described by Eqn. (65) found in Appendix A. This was carried out for both co and cross polarisation components. Illustrated in Fig. 154 are geometric examples of the modelled ash particles within CST MWS.

Also shown is the respective location of the elevation angle and polarisation planes used to define the different reflectivity data. Simulations have been carried out with the assumption that there is little moisture absorption within the particles, thus giving a representation of the lowest reflectivity state expected for ash. A total of eighty-five particles (i.e. 170 particle total) for both the random, chaotic and fluttering modes were simulated.

5.5.2 Simulated Reflectivity Results

The reflectivity of statistically correct ash particles that show geometrically, dynamically and electromagnetically correct distributions is presented within this section. The results from the CST MWS and MATLAB simulation have been presented in terms of the radar reflectivity ($\eta$), the differential reflectivity ($Z_{dr}=\eta_{vv}/\eta_{hh}$) and cross-polarisation reflectivity ($\eta_{vh}$). Here, all three parameters provide a complete representation of the scattering expected from ash created from a moderate temperature messmate eucalypt fire.

The measured effects of temperature on the mass of the eucalypt biomass allow for an accurate representation of each ash particle’s mass. This can then be used to extract the total particle concentration per unit volume. Information on the reflectivity of the modelled ash particles provides a basic understanding of the complex nature of the inverse scattering problem. It should also be noted that these results are idealised for the exact dynamic modes displayed by the ash particles. In reality, there may be a combination of a number of these modes.

The horizontal reflectivity for the simulation of the messmate ash particles displaying the fluttering and random chaotic modes is illustrated in Fig. 156.
Three elevation angles (0°, 45° and 90°) have been explored for the fluttering mode only. These elevation angles represent scattering that is common for vertical pointing (VPR) and scanning radar systems. VPR radar systems will observe scattering produced from the particles at 90° elevation and these have been seen in plume observations such as those described in [64-66]. Scanning radars located some distance from a fire source on the other hand, will observe scatter close to that produced from 0° elevation angles. It is assumed that the relative scatter for the chaotic random mode will be similar over all elevation angles. This is somewhat demonstrated by the random nature of the horizontal reflectivity seen in Fig. 156 d), as the concentration of particles increase. The overall reflectivity generated from the chaotic random mode shows similar trends to that of the 0°. As shown by the horizontal reflectivity over the three different elevation angles, the reflectivity increases as the wavelength decreases, for an increase in particle concentration. Clear concentration bands are distinguishable over all wavelengths. The 45° elevation angle shows the lowest return scatter under the fluttering mode. This is because at higher particle concentrations, the scatter is
reflected away from the transmitted signal. In other words, the bulk medium is acting as a partially flat reflective surface. The result of this is seen by the dramatic reduction in the reflectivity, in the order of $10\,\text{dBm}^2\cdot\text{m}^{-3}$ at 1 GHz to $30\,\text{dBm}^2\cdot\text{m}^{-3}$ at 40 GHz.

The lower frequency bands show almost negligible changes in the reflectivity with respect to the $0^\circ$ and $90^\circ$ elevation angle cases.

This is even true up to frequencies as high as 30 GHz. Beyond this frequency range, the reflectivity begins to diverge for the two cases to a point where there is an approximate $10\,\text{dBm}^2\cdot\text{m}^{-3}$ difference in the expected reflectivity at 40 GHz. This divergence is the result of the incident field at $90^\circ$ elevation angle. It is predominantly observing the edge effects of the ash particles causing lower overall reflectivity. This was demonstrated when analysing the individual RCS of ash in section 5.2.

The effects of polarisation for the same modelled particles are illustrated by the differential reflectivity, as shown in Fig. 156. Here, the effects of polarisation at $0^\circ$ and $90^\circ$ elevation angles show opposite trends at lower frequencies. As the frequency increases, differences in the reflectivity created by orthogonal polarised electromagnetic waves reduce. This reduction is likely to be the result of decreasing wavelengths of the incident field, relative to ash particle size. The $45^\circ$ is extremely random in nature, having a high amount of variation. This large variation can possibly be explained by the highly dispersive nature of the particle within this orientation. In other words, the interacting field is scattered more randomly than the other two cases. The simulated distribution of the differential reflectivity at lower frequencies and elevation angles is in line with observations made by Melnikov et. al. [54, 55]. Here, the differential reflectivity suggests horizontally oriented, needle-shaped particle geometry. This is because ash particles displaying the fluttering mode, regardless of their shape (as shown in section 3.8.2), will always be horizontally orientated. Also, due to the less than unity aspect ratio, planar ash is slightly elongated.

The random chaotic mode shows a much lower susceptibility to differences in the reflectivity for the given polarisations. This is expected, as the mixture of the dispersed ash particle should be by definition more homogeneous in nature. In this case, higher dispersion is also seen in the differential reflectivity at higher frequencies. These fluctuations are shown to be mostly generated from lower concentrations of ash. As more solid material is introduced into the scattering volume and the scattering field becomes stronger, the differential reflectivity trends towards 0dB.
Fig. 156 – Differential reflectivity ($\eta_{hh}/\eta_{vv}$) of messmate eucalypt ash over a wide range of frequencies where a) fluttering mode with beam elevation angle at 90°, b) fluttering mode with beam elevation angle at 45°, c) fluttering mode with beam elevation angle at 90° and d) random chaotic mode. Concentration (g/m^3) of the ash particles is represented by the colour of each point.

This is not seen in the fluttering modes where at lower frequencies, the differential reflectivity fluctuates higher based on increased concentration. As the frequency increases, the differential reflectivity also converges towards 0 dB as the concentration of ash particles increases.

Finally, the cross-polarisation reflectivity for the simulations is illustrated in
Fig. 157. Here, a clear link to the concentration of ash within the scattering volume can be made for all three cases. The three elevation angles under the fluttering mode show similar trends. The most pronounced feature between the two elevation angles is a slight flattening of the cross-polarisation response at 90° and 45° compared to 0°.

In contrast, the scattering created from the chaotic mode shows much higher cross-polarisation coupling to particle concentration when compared to the fluttering mode. This is to be expected, as the scattering in the chaotic mode will be more random in nature, leading to a greater cross-polarisation component detectable within the scattered field.
A comparison can be made between the reflectivity of snowflakes to that of ash particles. It is useful in many cases to describe the relative complex permittivity of ash in terms of its complex refractive index. The definition of the complex refractive index is given by Eqn. (33), where $n$ is the real component and $k$ is the imaginary component at each wavelength.

The relationships between the real and complex components of the relative complex permittivity to the respective are given by Eqn. (34) and Eqn. (35). This can be solved to find the relationship of the relative complex permittivity to the real and imaginary components of the complex index of refraction. These are given by Eqn. (36) and Eqn. (37), respectively.

\[
m(\lambda) = n(\lambda) - ik(\lambda)
\]

\[
e' = n^2 + k^2
\]

\[
e'' = 2nk
\]

\[
n = \sqrt{\frac{\sqrt{e'^2 + e''^2 + e'}}{2}}
\]

\[
k = \sqrt{\frac{\sqrt{e'^2 + e''^2 - e'}}{2}}
\]

Taking the median value of the effective exposed temperature distribution from section 0, the equivalent median relative complex permittivity is $\epsilon = 1.3 + i0.127$. Using Eqn (36) and Eqn. (37), an equivalent median complex refractive index for eucalypt ash is expected to be approximately $m = 1.1402 - i0.0056$ at X-Band. As shown by the linear response of the relative complex permittivity with frequency, this will be similar up to Ka-Band. Considering typical values of the refractive index of dry snowflakes, the complex refractive index is only
slightly higher in ash [206, 207]. These values are a consequence of the ash maintaining the majority of its internal structure once the volatile compounds have been removed at 450 °C. This has been illustrated by scanning electron microscope (SEM) images of ash analysed in section 3.6.4.2.

The concentration of larger ash particles within natural fires is still poorly understood, however; they will have the largest effects of the total scattering field. Measurements by Radke et. al. suggest ash particle concentrations for the larger particle spectrum concerned can range from $10^{-3}\text{cm}^{-3}$ to $10^{-7}\text{cm}^{-3}$, with effective diameters ranging between 0.1 mm and 10 mm [68, 69, 76, 115]. The concentration of these larger particles is however likely to change significantly, the further the particles travel from a main fire front. This forms part of the answer as to why high reflectivity is always seen at a fire source. The other being that the concentration of particles will be generally higher. The simulated reflectivity values thus demonstrate an initial analysis into the approximate value for the concentration of these larger ash particles from polarimetric measurements. This is key when analysing the inverse scattering case, however; further analysis and correlation to measurements will be required.

5.6 Conclusion

This chapter has discussed the fundamental scattering characteristics of ash particles. It has investigated the radar cross-section of standard geometric disks made of biomass. Accordance was shown between measured, simulated and theoretical results. The exploration into the RCS of two ash particles created within fires showed that the complex geometry of the particles begins to play a substantial role in the scattering above X-Band frequencies. Below this range, the particles fit well inside existing Rayleigh-based approximations over all incident angles. At Ka-band, it was shown that the formation of nulls is critical in accurately analysing the scattering of ash, especially when dynamic modes and incident angles are considered. Edge effects will be a dominant player in the scattering of the particles for scanning radar systems. Simulations of statistically correct ash particles displaying the three ideal dynamic conditions were finally explored. Here, differences in the polarimetric coefficients were explored.

This chapter has added to the body of knowledge by explicitly analysing the fundamental scattering mechanisms expected for planar ash particles. These scattering principles are critical for developing an inverse scattering model for the eucalypt species, which is the
primary genus of interest for Australia. The analysis broadly examines the expected scatter over a wire frequency range, which until now has been concentrated primarily at C and S Bands. Limited studies have explored X-Band and W-Bands. No observations have currently been made at Ka-Band.

Reviewing the remaining research question, there is no sign of coherent particle scatter causing lower frequencies to display higher coherent particle scatter. This is not to say it does not exist, however; the analysis has not shown this under static conditions. It is highly possible that higher order dynamic interaction is occurring if it can be shown to exist. The published data is still in its infancy and so this will only become apparent if a substantial number of radar measurements are taken over many different frequency bands.
Chapter 6 - Conclusion and Future Work

6.1 Conclusions

Understanding complex natural phenomena such as bushfires plays a significant role in assuring the safety of the wider community. Radar can provide a number of key functionalities to complement the suite of existing fire sensing technologies.

The aim of this dissertation was to investigate some of the principle scattering mechanisms behind the reflectivity of smoke plumes towards radar systems. Through the use of image processing, electromagnetic material characterisation and simulations a complete statistical representation of the scattering contributed from ash particulates has been explored over a broad range of frequencies. This analysis provides a fundamental background on the contribution of ash in scattering electromagnetic fields for use in both radar design and inverse scattering models.

6.1.1 Geometric and Dynamic Properties of Ash

The aim of this chapter was to investigate and develop a fundamental understanding of the geometric, dynamic and physical material characteristics of ash. The analysis was carried out for a number of genera which are important to Australia. The shape and size of larger ash particles are poorly described in literature. The statistical distributions of larger ash for the first time have been presented. It was shown that the reliance on flame temperature as a means of determining the properties of ash cannot be assumed. This is because there is too much variability in the physical material properties of the ash. This analysis has advanced the
body of knowledge by providing the statistical probability distribution functions for many types of ash.

In total eight different plant and tree species were analysed within this dissertation. This included two of the most populated genera in Australia; the eucalypt and acacias. Along with these two genera, investigations into needle foliage were also analysed with representative species from the pinus, cupressus and casuarina genera. With the aid of image processing statistical data sets were created which show many similarities between different genera. Examples of this were seen between the aspect ratio of eucalypt and acacia genera. Slight differences however were established in the projected areas of the particles which were found to be the result of the original foliage geometry. Mapping of the normalized mass loss and bulk density were also achieved in this chapter which have been shown to directly relate to the complex permittivity of the particles. This was confirmed in chapter 4.

Adding to this analysis was the investigation of the dynamic modes of the ash which have been previously unknown. Here, planar and needle shaped particles were analysed from the eucalypt and pinus genera respectively. The analysis of the horizontal orientation angle demonstrated that ash has a higher standard deviation compared to more symmetrical planar particles such as snowflakes. This was found to be the result of the highly asymmetrical geometry of the particles.

### 6.1.2 Complex Permittivity of Ash Particles

This chapter has provided the most significant gains to the body of knowledge. A complete map of the complex permittivity was achieved within this chapter. The complex permittivity was firstly map under controlled conditions. Here, the measurements were split into two effective temperature ranges being sampled at low temperature (*unburnt to 400 °C*) and high temperatures samples (*450 °C to 500 °C*). The low temperature samples were created from leaves exposed to specific temperature ranges using a hot plate. High temperature samples were created and their relative complex permittivity measured using powdered ash due to the fragility of the particles. In the low temperature samples a trend was observed with respect to the effective exposed temperature in four different species. The results of which were statistically indistinguishable from each other. The powdered ash also showed similar results with a projection of the expected permittivity and loss tangent made based on the bulk density of the biomass. The measured permittivity for the powdered ash
from all eight species was shown to follow an empirically derived mixing law where the
depolarisation ratio was shown to be same under all cases. Uncertainties in the solid density
of ash were shown to affect the inclusion permittivity required for the mixing law. This
uncertainty was the result of not being able to remove all voids within the powdered ash. An
investigation of the base permittivity of the biomass samples were analysed using a MicroCT
approach. Here, an optimised simulation approach based on 3D models extracted from
MicroCT were shown to have reasonably good results compared to the base permittivity
measured in both controlled and uncontrolled samples.

Finally a method of extracting the permittivity of an individual ash particle based on
image processing was proposed. It was shown that this method provides a good level of
agreement with controlled ash particles. Implementing two colour spaces and matching
methods showed agreement with the measured colour models. These colour models were
created for all eight species.

An effective exposed temperature distribution was then created for uncontrolled ash
particles for a moderate temperature eucalypt fire. The distribution showed that the majority
of the flying ash created from within the fire had a median effective exposed temperature of
approximately 425 °C. This effective exposed temperature distribution was correlated to the
complex permittivity via the proposed generalise permittivity model for ash. This generalised
model was showed to have excellent agreement with measurements and to explicitly follow
the normalised mass loss of the biomass. Here, the biomass of the four species samples were
shown to range from $\varepsilon = 2.3$ to $\varepsilon = 1.06$ at 450 °C. The trend in the permittivity of the burnt
biomass was shown to be an exponential reduction with increase in effective exposed
temperature. Beyond 450 °C the permittivity was shown to stabilise only reducing slowly
with increases in the effective temperature. The proposed image processing technique for
analysing the effective permittivity of ash has many practical uses in field testing.

6.1.3 Radar Cross-Section and Simulated Reflectivity

The final chapter investigated the radar cross-section and reflectivity of eucalypt biomass.
The analysis focused on implementing the knowledge gained from the previous chapters. The
analysis of the RCS of controlled biomass disks were measured using a wave guide method.
The method was used as a basis for validating simulated data at broadside. There was good
agreement between both measured and simulated results where the simulated data considered the generalised permittivity model.

Expanding on the 1D RCS measurements the 2D RCS for the disks was analysed using simulated and proven theoretical Kirchhoff method. Again, good agreement between the theoretical and simulated data was seen. The most noticeable difference was observed at large incident angles where the edge effects of the particles are not accounted for in theoretical approximations.

One of the most complex features to account for in ash was shown to be its inhomogeneous and anisotropic material behaviour. In the case of particles formed within fires multi-dielectric regions were shown to exist. An analysis was carried out to investigate the effects of the assuming generalised effective permittivity for a particle and the incorporation of multi-dielectric regions. Here, variations on the order of ±6 dBm² were noted. The largest variation was shown to occur within the formation of nulls at higher frequencies. At frequencies below X-Band the results showed excellent results. As the main error occurs at higher frequencies and at specific incident angles the model will also provide reasonable scattering data up to 40 GHz.

The reflectivity was then measured for eucalypt disks using a dynamic RCS measurement system. This system was housed inside a millimetre wave anechoic chamber and was fully PC controlled. The setup dispersed the particles evenly through a specific scattering region. The responses of the falling particles displaying the fluttering mode were tracked using a 240fps video camera. The video stream was then synced to the scattering response measured on a spectrum analyser. At locations of high reflectivity the numbers of particles were then counted from the video stream. The results of the measured reflectivity were then compared to simulated results. Here, the measured reflectivity was shown to have a reasonable correlation from the known upper deviation of the simulated data above the measurement noise floor.

Taking the confirmation of the simulated data for the disks a full EM simulation of statistically correct planar eucalypt ash particles were explored. This was achieved using a CST MWS and MATLAB program. The reflectivity was simulated for a dual polarisation state. The simulated data also investigated the effects of the different dynamic modes on the reflectivity under a case where the permittivity of the particles was assumed to have little if any moisture content. This presented the worst case scenario from a radar scattering perspective. This data also provided for the first time a look into the contributions of ash particles in the total scattering field. Distinguishable concentration bands were noted in the
cross-polarisation response of the models. This provides a good starting point for building an inverse scattering model.

### 6.2 Future Work and Concluding Remarks

Radar as a mature technology provides a capability which on a systems level is extremely unique for fire detection and monitoring applications. The known detectable scatter from bushfire plumes which have been documented within literature and within this dissertation have highlighted the ability of high powered meteorological radars to see fires. This has been achieved at extraordinary distances well beyond what is required for a practical system. In the case of remote monitoring of forests the implementation of these types of radars are neither practical nor viable due to power and infrastructure requirements. Currently there has been no investigation into low powered, short range radars for such applications.

Although radar operating in these bands have seen fire plumes and work is being carried out to implement detection algorithms for such platforms (*such as [41]*) , the problem really focuses on the end application. For long distance monitoring of fires traditional high powered ground based weather radar can satisfy most needs however they will have low sensitivity. In essence this will result in the need for fires to be of sufficient size before confirmation of a detectable scatter originating from a fire is made. This has been one of the hurdles restricting radar used in fire detection and monitoring applications since 1970’s [43]. If the Australian Black Saturday fires are used as an example, BoM weather radars were shown in chapter 2 to take in excess of 18 min to see the first signs of plume scatter from the Kilmore East fire after it started. This amount of time is too long for most practical fire remote sensing applications.

The next phase of research must focus on testing the viability of low powered wideband radar systems. These should focus at higher frequencies such as Ka-Band and W-Bands. The trade-off here is detection range however practically this does not need to be extensive. In complex terrain where there is limited line-of sight a maximum detectable range in the order of 10 - 20 km is more than sufficient. Either way it is recommended these systems have dual-polarisation capability it has been shown that the extraction of particle concentration is possible.

This research endeavoured to provide a fundamental background of the complexities involved in understanding scatter arising from smoke plumes. Focus was given to only scatter which arise from particulates only however this is only one small aspect of the total number
of scattering sources possible from fires. On the particle level ash has been shown to be an inherently complex medium consisting of multi dielectric phases, porosity and shapes.

Looking at the work carried out within this dissertation only the tip of the iceberg has been uncovered. A few areas of suggested future research will now be discussed.

### 6.2.1 Further Investigation on the Complex Permittivity of Ash

Although the complex permittivity of ash has been extensively reviewed within this dissertation it has only be characterised fully for two genera covering four species. The uncontrolled powdered ashes of the other genera only give an insight into those permittivity’s expected under limited burn conditions. To build on the current knowledge on the complex permittivity of ash further analysis is required in to other genera. This for example should include species not common to Australia. Particular focus should also be given to the analysis of the pinus genus as they are primarily used in forest plantations for soft wood products.

### 6.2.2 Permittivity Distribution from Bushfires

The analysis of the effective temperature distribution of eucalypt ash provided a means for correlating the generalised permittivity of each ash particle. This was achieved in chapter 4 for particles created within a burn chamber. To further analyse the complex permittivity of ash collections must be made from bushfires. This is a complex task as the particles are substantially fragile and they must be analysed in their full form to give the correct statistical distributions. The image processing techniques explored in this dissertation can be implemented to provide further knowledge on the geometric properties of larger ash created within fires.

### 6.2.3 Particle Concentration

One of the major unknowns about the reflectivity simulations is the concentration of larger ash particles present within a unit volume. For the smaller ash particle this has been well established however these larger particles only form close to the fire front and not analysis of their properties has been recorded. The use of aircraft in such measurements has been
successfully implemented (such as Radke et. al.) before however, the particle analysis here requires a fundamental understanding in all regions of a fire and plume column [68, 69, 76]. This poses a number of safety risks for human flight however the implementation of UAV’s in such research may present a number of benefits.

6.2.4 Validation of Scattering Models

The final chapter of this dissertation presented a method for simulating the reflectivity of statistically correct ash particles. One of the main uncertainties is the validity of the simulated data compared to measurements of open fires. Here, confirmation of the simulated scheme was achieved using controlled scattering models.

To truly validate the simulated models against real-world scattering will require extensive radar measurements over a number of bands. The difficulty arises in validating such data due to the unknown concentration levels of ash found in plumes. To overcome this, controlled measurements of scattering created from fires of similar biomass must firstly be explored.

6.2.5 Investigation of Other Scattering Sources

Future work will also require an understanding of other scattering sources within fires. For example clear air scattering is known to be a significant contributor at higher frequencies. This will become a critical player if millimetre wave band radars are utilised in fire detection and monitoring fields. Along with this the characterisation of moisture content within plumes needs investigating further. It’s known that fires can produce rain if sufficient water content is available within burning biomass. Within Australia this is not generally the case in small ground fires however crowning fires which consume hydrated vegetation may result in particle saturations level not seen in the lab testing. The mechanisms for moisture absorption are presented within the larger ash particles.
APPENDIX

A. Review of Electromagnetics and Radar Fundamentals

Interaction of Electromagnetic Fields within Mediums

The fundamental interactions between electromagnetic waves and scattering mediums such as those found in smoke plumes are of most importance when understanding the return echoes to radars. In the study of a scattering electromagnetic wave the material properties of the medium being investigated needs detailed exploration. These interactions take two forms which include those on the macroscopic level which describe the behaviour of the material as a whole and those on the microscopic level which look at the interactions on an atomic level. When a propagating electromagnetic wave hits a medium the interacting field causes a slight displacement in each charge particle. This displacement of the field on the macroscopic level is caused by the polarisation of the medium which sets up opposing electric and magnetic fields [208]. On the microscopic level this can be explained by the energy bands required to change the state of electrons and magnetic moments of atoms making up the medium [140].

Looking specifically at the solid constituents of fires, little is known about the material properties of ash particles in the microwave region of the electromagnetic spectrum [34, 38, 54, 55, 64-66]. On the macroscopic level, assuming time harmonic propagation, the interactions of electromagnetic waves and a material can be described by Maxwell’s equations. In phasor form these are given as [208-210]:

\[ \nabla \times \mathbf{E} = -j\omega \mathbf{B} - \mathbf{M} \]
\[ \nabla \times \mathbf{H} = j\omega \mathbf{B} + \mathbf{J} \]
\[ \nabla \cdot \mathbf{D} = \rho_v \]
∇ \cdot \mathbf{B} = 0 \quad (41)

Where \( \mathbf{E} \) represents the electric field (V/m), \( \mathbf{B} \) represents the magnetic flux density (T/m²), \( \mathbf{M} \) represents the magnetization (A/m), \( \mathbf{H} \) represents the magnetic field strength (A/m), \( \mathbf{J} \) represents the electric current density (A/m²), \( \mathbf{D} \) represents the electric flux (C/m²), \( \rho_V \) represents the electric charge density (C/m³) and \( \omega \) is the angular frequency given by \( 2\pi f \), where \( f \) is the frequency of the electromagnetic wave (Hz). \( \nabla \) is the del operator representing the curl (\( \nabla \times \)) or div (\( \nabla \cdot \)) of the vector space. Both the electric and magnetic fields are represented in 3-dimensional space thus each bold component in Maxwell’s equations signifies a 3D vector (i.e. \( \mathbf{E} = E_x \mathbf{e}_x + E_y \mathbf{e}_y + E_z \mathbf{e}_z \)). The magnetic charge density (\( \rho_{mV} \)) and current density (\( \mathbf{M} \)) do not exist in reality and are introduced mathematically to create symmetry in Maxwell’s equations [208, 210].

The response of different materials to electromagnetic fields is also highly dependent on its linearity, homogeneity and isotropy. Linearity describes the response of a material to different field strengths. For the majority of radar related applications most materials will act linearly as the field strength is not large enough to see any non-linear effects appear. The homogeneity of a material describes how the electromagnetic field acts within each region of the materials physical volume. All materials have various degrees of inhomogeneity which are more prevalent to those arising from naturally forming materials [140]. Finally the isotropy of the material describes how the field interacts when propagating from different directions. Materials with anisotropic properties are generally described by what is known as a dyadic tensor matrix which describes the relative complex permittivity and permeability in all three physical dimensions of space.

The displacement in the electric and magnetic fields relative to the corresponding flux densities due to the propagation through a polarising material can be expressed by introducing what is termed the permittivity (\( \varepsilon \)) and permeability (\( \mu \)). The permittivity and permeability of a material are related electrically and magnetically by the following relationships:

\[
\mathbf{D} = \varepsilon \mathbf{E} = \varepsilon_0 \mathbf{E} + \mathbf{P}_e
\]

\[
\mathbf{B} = \mu \mathbf{H} = \mu_0 (\mathbf{H} + \mathbf{M})
\]
Appendix

Where \( \varepsilon \) is the permittivity of a medium, \( \varepsilon_0 \) is the permittivity of free space (vacuum), \( \mu \) is the permeability of a medium, \( \mu_0 \) is the permeability of free space (vacuum) and \( P_e \) is the electric polarization.

\[
e_0 = 8.854 \times 10^{-12} \equiv \frac{10^{-9}}{36\pi} \, F. \, m^{-1}
\]  
(44)

\[
\mu_0 = 4\pi \times 10^{-7} \, H. \, m^{-1}
\]  
(45)

\[
P_e = (\varepsilon - \varepsilon_0)E = \varepsilon_0\chi_eE
\]  
(46)

Where \( \chi_e \) is the electric susceptibility which is also expressed as:

\[
\chi_e = \frac{1}{\varepsilon_0} \frac{P}{E}
\]  
(47)

Due to the very small number involved with calculating the permittivity and permeability, the values are converted into a ratio termed the relative permittivity (\( \varepsilon_r \)) and permeability (\( \mu_r \)). These have the following relationship to the permittivity and permeability of free space:

\[
\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = 1 + \chi_e
\]  
(48)

\[
\mu_r = \frac{\mu}{\mu_0}
\]  
(49)

The permittivity and permeability are complex numbers and thus there real and imaginary components represent the displacement and loss of the field within a medium. These are given as:

\[
\varepsilon_r = \varepsilon_r' - j\varepsilon_r''
\]  
(50)

\[
\mu_r = \mu_r' - j\mu_r''
\]  
(51)
The loss is further expressed in terms of the electric \((\tan \delta_e)\) and magnetic \((\tan \delta_m)\) loss tangent given as:

\[
\tan \delta_e = \frac{\varepsilon_r''}{\varepsilon_r'}
\]  
(52)

\[
\tan \delta_m = \frac{\mu_r''}{\mu_r'}
\]  
(53)

Where a material exhibits both electric and magnetic losses the total loss tangent is given as [147, 148]:-

\[
\tan \delta = \frac{\delta_r''}{\delta_r'}
\]  
(54)

Where:

\[
\delta_r' = \varepsilon_r' \mu_r' - \varepsilon_r'' \mu_r''
\]  
(55)

\[
\delta_r'' = \varepsilon_r'' \mu_r' + \varepsilon_r' \mu_r''
\]  
(56)

**Radar Fundamentals**

Radar, on a systems level is generally bound by the types of waveforms being transmitted. These waveforms are a direct result of the intended application or scenario for which the radar will operate. In the basic sense, there are two main waveform classifications. These waveform classifications are pulsed and continuous wave (CW). Both waveform types suit a variety of different applications including the detection of dispersed mediums such as ash particles.

Pulsed radar systems have been extensively used since the birth of radar during the late 1930’s, early 1940’s. Even in many modern radar systems such as weather radars, pulsed waveforms are still extensively utilised due to their relatively simple signal processing. These
systems are characterised a narrow band systems which operate with a spectral bandwidth in the order of 2-5MHz. The RF front end is simple in design and high powered magnetrons, klystrons or traveling wave tubes (TWT’s) can be used to generate pulses of several tens to hundreds of kilowatts in peak transmit power [211, 212].

Continuous wave radar can be found in two sub-categories which are defined as non-modulated and modulated waveforms. A non-modulated system transmits a constant tone which can only be used to extract Doppler information about a target. Modulated systems apply a modulation scheme to the waveform to allow the extraction of range information. Modulation schemes vary extensity with the application of the radar however these are defined as amplitude modulation (AM), frequency modulation (FM) and phase modulation (PM). Typically FM and PM modulation schemes or a combination of the two are used to form the signal synthesis of modern modulated CW radar systems. The principles behind modulated continuous wave radars date back to the late 1920’s [213]. They were typically restricted to distance measuring systems such as radio altimeters for aircraft. It has only been within the past few decades that their popularity has increased due to the availability of high power, wideband MMIC technology and computing power allowing signal processing to be completely carried out in the digital domain.

Before any of the research questions outlined in section 2.5.1 can be answered, the basic principle of radar must be discussed. The radar performance parameter of most importance is the radar cross-section (RCS). This parameter is best described by the radar range equation given by Eqn. (59).

\[
P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 K_b T_0 N_f B L}
\]

(57)

Where:-

- \( P_t \) = Transmitted power (W)
- \( G \) = Antenna Gain (dBi)
- \( \sigma \) = Radar Cross-Section (m²)
- \( K_b \) = Boltzmann’s Constant (1.3806488e-23 m² kg s⁻² K⁻¹)
- \( T_0 \) = Ambient Temperature of Free-Space (K)
- \( N_f \) = System Noise Figure (dB)
- \( B \) = Receiver Bandwidth (Hz)
- \( R \) = One-Way Range (m)
- \( L \) = Loss Factor (dB) – system and fluctuations
The radar range equation describes all the system gains and losses including free-space loss and thermal noise which can affect the propagation of an electromagnetic signal as well as the sensitivity of the receiver. If all other system parameters are known the radar cross-section can be solved. Unique properties of electromagnetic waves are their polarizability which also affects the evaluation of the radar cross-section.

The polarisation of a radar antenna defines the polarisation of both the transmitted and received signals. These are generally identical for mono-static radars *(single antenna used for both transmit and receive)* however may change in the case of bi-static radar *(separate antennas used for both transmit and receive)* or intended application. Electromagnetic waves are commonly defined as being linear or circular polarised, however this may also include elliptically polarised waves. Linear polarised waves are defined as “electromagnetic waves for which the locus of the tip of the electric field vectors is a straight line in a plane orthogonal to the wave normal” [10]. Linear polarised fields are generally described as being ‘horizontally (H)’ or ‘vertically (V)’ polarised. This refers to the orientation of the electric field vector relative to the earth surface *(i.e horizontal polarised waves are parallel, vertical polarised waves are perpendicular)*. Circular polarised waves on the other hand are defined as “electromagnetic waves for which the locus of the tip of the instantaneous electric field vector is a circle in a plane orthogonal to the wave normal” [10]. These are found in two propagation forms called left and right-hand circular polarization *(LCP, RCP)*. Elliptical polarised waves follow the same convention whereby the locus of the electric field vector is elliptical in shape. A reflected linear polarised electromagnetic wave can be received using an antenna of equivalent polarisation *(i.e P_{t V} → P_{r V}, P_{t H} → P_{r H})*. A reflected circular or elliptical polarised electromagnetic wave must be received using an antenna of opposite circular polarisation *(i.e P_{t LCP} → P_{r RCP}, P_{t RCP} → P_{r LCP})*.

Solving the RCS in the case of a linear polarised field required the scattered incident field to be of the same polarisation as the receive antenna. This polarised field, also known as the principal field, may not always be the only scattered field present at the receive antenna however, will be the only detectable field couples into the antenna structure. In the case of linear polarised antennas detecting circular polarized electromagnetic waves, a 3bB loss is incurred due to half the power being present in the orthogonal polarisation plane. To determine more information about a scattered field, it is common practice to implement what is termed a polarimetric measurement. This measurement takes advantage of different polarisation reflections of a target similar to the way polarise lenses are used in cameras. Here, the principle, orthogonal and cross-polarised fields are measured. The result of this
measurement allows for the determination of what is termed the total backscattered RCS matrix (see Eqn. (60)). This total backscatter matrix is related to the scattering matrix in terms of polarisation by Eqn. (62). Finally, the relationship between the electric field in both orthogonal polarisations and the scattering matrix for the incident \(E^i\) and scatter \(E^s\) fields is given in Eqn. (62) [63, 211].

\[
\begin{bmatrix}
\sigma_{11} & \sigma_{12} \\
\sigma_{21} & \sigma_{22}
\end{bmatrix}
= \begin{bmatrix}
\sigma_{HH} & \sigma_{HV} \\
\sigma_{VH} & \sigma_{VV}
\end{bmatrix}
= 4\pi R^2 \begin{bmatrix}
|S_{11}^2| & |S_{12}^2| \\
|S_{21}^2| & |S_{22}^2|
\end{bmatrix}
= 4\pi / k \begin{bmatrix}
|S_{11}|^2 & |S_{12}|^2 \\
|S_{21}|^2 & |S_{22}|^2
\end{bmatrix}
\]

(58)

Where:- \(k\) is the wave number \((k = 2\pi/\lambda)\)

\[
[S] = \begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}
= \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix}
\]

(59)

\[
\begin{bmatrix}
E^s_H \\
E^s_V
\end{bmatrix}
= \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix}
\begin{bmatrix}
E^i_H \\
E^i_V
\end{bmatrix}
\]

(60)

In the case of dispersed or volume targets such as those presented by fire ash, the RCS takes on a variant form known as volume scatter. The volume scatter or volumetric radar cross-section is representative of the sum of the scatters inside a resolute volume. It represents the total backscatter of the dispersed targets as given by Eqn. (63). The resolute volume \((V_m)\) is characterised by the half-power beamwidth of the antennas radiation pattern in both E and H planes (azimuth \((\theta)\) and elevation \((\phi)\)), the range \((R)\) and the range resolution of the radar \((\Delta R)\) (see Fig. 163). Due to the Gaussian shape of antenna radiation patterns (as illustrated in Fig. 164), and the asymmetry of the power density over the resolute volume, a correction must be made. The Gaussian correction is using a sinc function as defined by Eqn. (66). Finally, the total scatter \(\sigma_{total}\) produced by a resolute volume is given by the average reflectivity of the dispersed targets within the resolute volume. Eqn. (67).
Fig. 158 – Illustration of the resolute volume for a scattering volume

\[ \eta = \sum_{i=1}^{N} \sigma_i \ (m^2) \]  
\[ (61) \]

\[ V_m = \frac{\pi \Delta R R^2 \tan(\Theta) \tan(\Phi)}{4} \quad (m^3) \]
\[ (62) \]

\[ \Delta R_{\text{pulse}} = \frac{ct}{2} \ , \quad \Delta R_{\text{fmcw}} = \frac{c}{2B} \]
\[ (63) \]

\[ f_{\text{Gaussian}} = \frac{1}{2\ln(2)} \]
\[ (64) \]

\[ \sigma_{\text{total}} = \sum_{i=1}^{N} \sigma_i V_m = \eta V_m \]
\[ (65) \]

Fig. 159 – Example of an antennas farfield radiation pattern with colour map of realized gain.
The total RCS only represents the energy which is scattered back towards a radar system. This however does not include the scattering of the electromagnetic waves in other directions or the contributions of dielectric or magnetic loss caused by the propagation of the electrometric field through the dispersed medium. To describe this energy lost the extinction cross-section ($\sigma_e$) is introduced and is given by (68).

$$\sigma_e = \sigma_\alpha + \sigma_{ts}$$  \hspace{1cm} (66)

Where $\sigma_\alpha$ is the absorption cross section representing the losses from the imaginary components of the relative complex permittivity and permeability of a material and $\sigma_{ts}$ is the total scattering cross section representing the loss due to scattering alone.

**Theoretical Kirchhoff Wideband Mono-Static 2D Radar Cross-Section of Ash Particles**

A comparison between the CST MWS mono-static RCS simulations of the ash disks (see chapter 5) and that predicted by theory will be given in this section. A modified Kirchhoff type scattering approximation using a Fourier transform is given by Le Vines and will be investigated for its comparison to the simulated scattering of a thin dielectric disk [194, 195]. This can be solved analytically based on geometry and permittivity of the disk. It uses a combination of both a sinc and first order Bessel. Here, the sinc function is used to shape the Bessel function. After deviation Le Vines showed the horizontal and vertical mono-static radar cross section can be approximated by Eqn. (69) and Eqn. (70) respectively.

$$\sigma_{hh} = (S_{hh} \cdot \tilde{S}_{hh}) \ast (S(\tilde{\nu}t) \cdot \tilde{S}(\tilde{\nu}t))$$  \hspace{1cm} (67)

$$\sigma_{vv} = (S_{vv} \cdot \tilde{S}_{vv}) \ast (S(\tilde{\nu}t) \cdot \tilde{S}(\tilde{\nu}t))$$  \hspace{1cm} (68)

Where $\tilde{S}_{hh}$ and $\tilde{S}_{vv}$ are the complex conjugates of $S_{hh}$ and $S_{vv}$ and $\tilde{S}(\tilde{\nu}t)$ is the complex conjugate of $S(\tilde{\nu}t)$. $S(\tilde{\nu}t)$ is given by Eqn. (71).

$$S(\tilde{\nu}t) = \frac{\pi a^2 J_1(A)}{k_0 a \cdot \sin(\theta)}$$  \hspace{1cm} (69)
Appendix

Where \( J_1 \) is the first order Bessel function of \( A \) (see Eqn. (71)), \( a \) is the radius of the disk, \( T \) is the thickness of the disk, \( k_0 \) is the free-space wave number \( (k_0=2\pi/\lambda) \) and \( \theta \) is the respective incident angle.

\[
A = 2k_0 \sin(\theta)
\]

(70)

Finally, the coefficients for a circular disk are given as:-

\[
S_{hh} = \left\{ \left[ \text{sinc}(\alpha \Omega_+) - r_h e^{(j2\pi r)} \sin c(\alpha \Omega_-) \right] \hat{\varepsilon}_h S_0 \right\}
\]

(71)

\[
S_{vv} = \left\{ \left[ \gamma_+ \text{sinc}(\alpha \Omega_+) - r_v e^{(j2\pi r)} \gamma_- \sin c(\alpha \Omega_-) \right] \frac{\hat{\varepsilon}_v}{\sqrt{\varepsilon_r}} S_0 \right\}
\]

(72)

and,

\[
\alpha = \frac{1}{2k_0 T} \quad S_0 = \frac{1}{\sqrt{4\pi \varepsilon_r}} Tk_0^2 (\varepsilon_r - 1) \quad \Omega_\mp = \cos(\theta) \mp \Gamma \quad \gamma_\mp = \sin^2(\theta) \mp \cos(\theta) \Gamma
\]

\[
\Gamma = \sqrt{\varepsilon_r - \sin^2(\theta)} \quad \hat{\varepsilon}_{h,v} = \frac{t_{h,v} e^{(-j\alpha \Omega_-)}}{1 - r_{h,v} e^{(j2\pi r)}} \quad r_{h,v} = \frac{\cos(\theta) - \xi_{h,v} \Gamma}{\cos(\theta) + \xi_{h,v} \Gamma} \quad t_{h,v} = \frac{2\cos(\theta)}{\cos(\theta) + \xi_{h,v} \Gamma} \sqrt{\xi_{h,v}}
\]

Where \( \xi_h = 1 \) and \( \xi_v = 1/\varepsilon_r \). The resultant theoretical wideband response of ash over four of the exposed temperature ranges (200°C, 300°C, 400°C and 500°C) in horizontal polarisation have been presented in Fig. 126. The equivalent vertical polarisation is illustrated in this model shows a very good approximation of the 2D mono-static RCS of the dielectric disks. The 0° incident angle shows good agreement with the 1D measured and simulated mono-static results. This Kirchhoff model is known to neglects edge effects which results in an induced error at larger incident angles. The result of neglecting the edge effects is illustrated by the missing scatter data present at ±90° incidents in the horizontal and vertical polarisation. Both the horizontal and vertical data are similar as by definition the cross-polarisation component must be \( \sigma_{v,h} = \sigma_{n,v} = 0 \).

This is also seen by the distinct differences between the Kirchhoff model and CST MWS simulations at the larger incident angles. The null locations are also seen to be extremely similar in both cases. Kirchhoff approximation provides a quick first order approximation of the 2D mono-static RCS of the ash if generalised disk geometry is assume.
Fig. 160 – Theoretical horizontally polarised 2D mono-static RCS ($\sigma_{hh}$) of the L-Disks of messmate eucalypt ash with the geometric and RF properties outlined in Table 17 with respect to frequency. a) 200°C, b) 300°C, c) 400°C, and d) 500°C
Fig. 161 – Theoretical 2D vertically polarised mono-static RCS ($\sigma_m$) of the L-Disks of messmate eucalypt ash with the geometric and RF properties outlined in Table 17 with respect to frequency. a) 200°C, b) 300°C, c) 400°C, and d) 500°C

**Probability Distribution Functions (PDF)**

**Generalized Pareto distribution**

$$f(x) = \left( 1 + \frac{x}{\sigma} \right)^{-1-\frac{1}{\tau}}$$

(73)

**Normal distribution**

$$f(x) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left( -\frac{(x-\mu)^2}{2\sigma^2} \right)$$

(74)

**Generalized extreme value distribution**

$$f(x) = \frac{1}{\sigma} \exp \left( \left( 1 + \frac{x-\mu}{\sigma} \right)^{-\frac{1}{\tau}} \right) \left( 1 + \frac{x-\mu}{\sigma} \right)^{-1-\frac{1}{\tau}}$$

(75)
Extended Debye Model for Water to 100 GHz with temperature dependency

The relative complex permittivity of water used in the predictive models for the dielectric mixing law will be outlined here. The relative complex permittivity of water has a good relationship to the Debye relationship which defines the permittivity of a material with respect to its static permittivity ($\varepsilon_s$), optical permittivity ($\varepsilon_\infty$) and its relaxation time ($\tau$). Recently released semi-empirical modelling has been successful at modelling the relative complex permittivity of water to 100GHz with the lowest RSM error of all previous Debye type models [214]. The relative complex permittivity can be expressed in two ways given as:

$$\varepsilon(f_{GHz}) = \sum_i \Delta_i * F_i(f_{GHz}) + \varepsilon_\infty = \varepsilon_s - \sum_i \Delta_i * [1 - F_i(f_{GHz})]$$

(76)

Where $F_i$ is a normalised complex shape function describing the permittivity in different regions of the EM spectrum and $f$ is the frequency in GHz (1e9 Hz). Two shaping functions are given for this model designated as $F_R$ and $F_B$ which define the regions where Raman Scattering (R) and Intermolecular vibrational bending modes (B) are present (refer to [214] for further details).

The static permittivity ($\varepsilon_s$) is related to the optical permittivity ($\varepsilon_\infty$) via:

$$\varepsilon_\infty = \varepsilon_s - \sum_i \Delta_i$$

(77)

The two complex shaping functions $F_R$ and $F_B$ are given as:

$$F_R(f_{GHz}) = \frac{\gamma_R}{\gamma_R + i.f_{GHz}}$$

(78)

$$F_B(f_{GHz}) = \frac{\log\left[\frac{z_2 - i.f_{GHz}}{z_1 - i.f_{GHz}}\right]}{2\log\left(\frac{z_2}{z_1}\right)} + \frac{\log\left[\frac{z_2^* - i.f_{GHz}}{z_1^* - i.f_{GHz}}\right]}{2\log\left(\frac{z_2^*}{z_1^*}\right)}$$

(79)

Where $z_i^*$ is the complex conjugate of $z_i$ to satisfy the Kramers-Kronig relation for materials. The static permittivity is given by:
\[ \varepsilon_s = -43.7527 \theta^{0.05} + 299.5040 \theta^{1.47} - 399.364 \theta^{2.11} + 221.327 \theta^{2.31} \]  

(80)

Where

\[ \theta = \frac{300}{(T + 273.15)} \]  

(81)

And T is the temperature of the liquid in degrees centigrade (°C). Finally the remaining coefficient are given as:

\[ \Delta_R = 80.69715 \exp\left(-\frac{T}{266.45}\right) \]  

(82)

\[ \gamma_R = 1164.023 \exp\left(-\frac{651.4728}{T + 133.07}\right) \]  

(83)

\[ \Delta_B = 4.008724 \exp\left(-\frac{T}{103.05}\right) \]  

(84)

\[ z_1 = (-0.75 + i) \nu_1 \]  

(85)

\[ \nu_1 = 10.46012 + 0.1454962T + 0.063267156T^2 + 0.00093786645T^3 \]  

(86)

and

\[ z_2 = -4500 + i2000 \]  

(87)
B. Tree and Plant Species

Eucalyptus Genus

Messmate Stringybark (Eucalyptus obliqua)

Fig. 162 – Messmate Eucalypt (Eucalyptus obliqua), a) large red Messmate eucalypt tree, b) example of foliage, c) example of the texture and colour of the bark, c) seed pods, d) top side of leaves, and e) under-side of leaves.
Red Ironbark (Eucalyptus tricarpa)

Fig. 163 - Red Ironbark (Eucalyptus tricarpa), a) large red Ironbark tree, b) example of the texture and colour of the bark, c) texture and colour of branches and seed pods, d) top side of leaves, and e) under-side of leaves.
Spotted Gum (Eucalyptus maculata)

Fig. 164 - Spotted Gum (Eucalyptus maculata), a) large spotted gum tree, b) example of the texture and colour of the main trunk, c) texture and colour of branches, d) top side of leave, and e) under-side of leaves.
Acacia Genus

Fig. 165 – Blackwood Wattle (Acacia melanoxylon), a) example of a juvenile tree, b) example of a juvenile seedling, c) colour and texture of the bark, d) example of the foliage, e) length of a single needle
**Pteridium Genus**

**Austral Bracken Fern (Pteridium esculentum)**

*Fig. 16 – Austral Bracken Fern (Pteridium esculentum), a) single fern in its natural ecosystem, b) example of a highly populated Bracken Fern population, c) texture and colour of the stem, d) top side of leaf, and e) under-side of leaves.*
Casuarina Genus

6.2.5.1 Swamp Sheoak (Casuarina glauca)

Fig. 167 - Sheoak (Casuarina glauca), a) example of a mature sheoak tree, b) example of a juvenile sheoak tree, c) colour and texture of the bark, d) example of the foliage, e) length of a single needle, e) example of the seed pods.
Pinus Genus

Radiata Pine (Pinus Radiata)

Fig. 168 - Radiata Pine (Pinus Radiata), a) example of the radiate pine bark, b) foliage of the pine, c) pine cone, d) example of the pine needles, e) examples of a radiate pine plantation in the Otway’s Victoria
Cupressus Genus

Cypress (Cupressus Leylandii)

Fig. 169 - Cypress (Cupressus Leylandii), a) example of a Leyland Cypress tree, b) example of seed pod, c) colour and texture of the bark, d) example of the foliage, e) length of a single needle
C. Image Processing Techniques

The task of analysing individual ash particles and acquiring large enough data sets to correctly describe their geometric properties statistically is an enormous task. Image processing is a technique which can help solve many of these tedious tasks. Image processing takes many forms, however it is typically used to extract information about an object(s) of interest based on pixel count, pixel shading and/or pixel colour. It is not limited to just single frame images with the technique commonly used in biology sciences to track the movement of bacteria and cells from video footage.

The image processing techniques used within this dissertation relay on a program called ImageJ. ImageJ is an open source image processing software package supported by the National Institute of Health (NIH) [202]. The package is a Java based program providing macro/script based coding and is easily configured to automate many different image processing tasks.

Given the properties of ash to be analysed (as outlined in Fig. 9), image processing can fulfil most of the tasks required for understanding their geometric characteristics. It has the capability to analyse the projected surface area of the particles as well as their aspect ratio. These two properties give a good estimation of the volume a particle will occupy in free-space. On top of this, colour matching can be used to find statistical links between the maximum exposed temperature of an individual ash particle and their RF material properties. This bypasses the problems highlighted with relying on flame temperature as a means of determining the material properties and hence the scattering properties of ash.

Image processing will be utilised extensively throughout this dissertation. This section will provide a complete overview of the image processing methodology. A flow chart of the complete image processing method is demonstrated in Fig. 170.
Fig. 170 - Outline of image correlation/matching process used to determine the PDF and error model of fire generated particles.

Once the ash samples have been collected the first image processing step involves the generation of suitable images for extracting useful information. To extract information such as area and aspect ratio considerations on the perspective angle of an image must be made. To reduce the effects of field depth and changes in perspective view, a scanning type arrangement is preferable.

To achieve this for the ash samples to be analysed, a high resolution Canon CanoScan LiDE 600F document scanner was employed to carry out the majority of the imaging tasks. Also, using a single scanner reduces the variability in image resolution and colour quality (i.e. contrast, brightness, saturation, hue, etc.). To achieve the best quality images possible, scans were taken at 1200 dpi resolution. Once the scanning process was completed the second image processing step involves a pre-processing stage. This stage details processes such as
removing unwanted background information and cleaning the images of pixel noise. This is a partly manual step and was carried out using pre-existing features found in Adobe Photoshop©.

The extraction of projected surface area and aspect ratio are carried out using pre-existing ImageJ scripts. To accurately measure the surface area all the scanned images must be accurately scaled. Images in tiff format are generally embedded with the scanners conversion factor for describing the ratio between pixel and length. To check this, a steel ruler was also placed along one edge of each of the scanned images to ensure the embedded scale factor was correct. The extraction of surface area is carried out within ImageJ by simply extrapolating the number of pixels present within a defined region. This number of pixels is then scaled by the required scaling factor. The region for defining where the pixels are to be counted is achieved by applying a threshold mask on top of the required particles. Once the projected area has been extracted, ImageJ then fits an ellipse to the particles of interest. The major and minor axis of the ellipse is then used to calculate the aspect ratio of the particles. The definition of the projected area, aspect ratio and thickness used to describe planar and needle type ash particles within this dissertation is given in Fig. 171 and Fig. 172 respectively.

\[
AR = \frac{\text{Min. Axis}}{\text{Maj. Axis}}
\]

Fig. 171 – Definition of the projected area, aspect ratio thickness for planar type ash particles

\[
AR = \frac{\text{Min. Axis}}{\text{Maj. Axis}}
\]

Fig. 172 – Definition of the projected area, aspect ratio thickness for needle type ash particles
Apart from the scanned images of ash some Digital Single-Lens Reflex camera photos were also used for image processing. These images followed the same post-processing method outlined however are subjected to some error due to the perspective viewing angle induced by the position of the camera.

**Image Normalisation Process**

One of the drawbacks with using raw images for image processing is the large variation in pixel illuminations which can exist after the scanning process. These variations are primarily caused by shadowing and/or reflectivity effects created during the scanning process and can severely degrade colour information. These effects are a direct result of the light source being at a different location to the imaging sensor of the scanner, and are unavoidable. For particles with relatively large projected areas, these variations in illumination have less of an effect on the quality of the data that can be gathered. However, as the particles area reduces the quality of data also progressively degrades.

To remove the effects of variation in illumination, an image normalisation process must be carried out prior to commencing any image processing. This normalisation process removed the effects of the illumination by levelling the intensities of each colour channel [192, 203]. The normalization process carried out on all the raw images of ash is described in Eqn. (88). An example showing the effects of shadowing and reflection on an original raw scanned image and the resultant normalized image are illustrated in Fig. 173.

The normalization process shows a clear reduction in the variations of illumination caused by shadowing effects within the image. The normalization process was implemented via a custom macro running through ImageJ. A copy of the image normalisation macro can be found in Appendix E.
\[ I_n = \frac{V_{rgb}}{\sqrt{V_r^2 + V_g^2 + V_b^2}} \] (88)

Where:
- \( I_n \) is the normalized pixel for each R, G or B value
- \( V_{rgb} \) is the R, G or B pixel value
- \( V_r \) is the red channel value
- \( V_g \) is the green channel value
- \( V_b \) is the blue channel value

Fig. 173 - Example of an a) high resolution scan of a dried eucalypt leaf showing small variation in illumination created during the scanning process (image is an enlargements of a 3.4mm x 3.4mm patch), b) same image with implementation of the pixel normalization process.

**Image Processing Technique for Maximum Expose Temperature**

The average colour of ash has been shown to have some degree of correlation to its exposed temperature [78, 110, 112, 188]. This colour correlation to temperature however is not consistent between different tree and plant species [78].

Taking the assumptions that an individual ash particle acts as an effective homogeneous material at typical radar operating wavelengths (which will be discussed further in chapter 4), the average exposed temperature distribution of an ash particle can be approximated. This temperature distribution is required as the complex permittivity will vary slightly for each ash particle created within a fire. By mapping the effective complex permittivity against exposed temperature a link between physical ash created within fires and an approximation of
their effective complex permittivity values can be made (see Fig. 174). Image processing can again be used to extract this temperature information about ash.

![Flow chart showing the relative steps required to ascertain a distribution for the complex permittivity of an individual ash particle based on its exposed temperature](image)

The first step in implementing any colour matching techniques is to build colour models which describe how different biomass structures change colour with temperature. Here, a focus has been placed on the leaf structures of the plant and tree species outlined in section 3.2. Controlled leaf specimens were firstly collected, pressed until dry and finally exposed at controlled temperature ranges of $150^\circ C$ to $600^\circ C$ at $50^\circ C$ increments. A specimen of the original biomass was also measured as a starting point for the model. The exposed specimens were then scanned, pre-processed and normalized as per the image processing method outlined in Fig. 170. The average normalized RGB values from each pixel of the biomass specimens were then extracted at the given temperature ranges. Each specimen for each of the temperature ranges consisted of a projected surface area greater than 1000 mm$^2$. This represented a minimum pixel count of 2.3 million at the given resolution. On average there were 12 leaf specimens tested for each of the temperature ranges. A cubic extrapolated model of the normalized mean RGB values for messmate eucalypt leaves at the given temperature ranges are illustrated in Fig. 175. The complete set of normalized mean RGB models for the remaining plant and tree species outlined in section 3.2 can be found in Appendix D.

The overall normalized RGB values show clear differences between the un-burnt states to those exposed at 600$^\circ C$. At low temperatures ($\leq 200^\circ C$) there are significant differences between each RGB channel. At higher temperatures ($\geq 250^\circ C$) the RGB values start to converge. The 450$^\circ C$ mark represents the temperature at which the biomass first begins to ember. Beyond this temperature the biomass has sufficient energy to maintain a flame until all its volatile compounds have been removed. This is shown by the rapid change in all three
channels. Once this ember and flaming stage is completed, the colour of the particles remains fairly consistent. To remove any uncertainties in matching ash from fire to the RGB models, an alternative colour space model was implemented. The second colour space is based on the International Commission on Illuminations (CIE) LAB colour space. In LAB space the ‘L’ represents the lightness while the ‘A’ and ‘B’ components represent the colour-opponent dimensions. CIELAB has a number of advantages or RGB space models however the most important of which is its device independency. This is unlike the original RGB model which is defined by the response of the scanner resulting in the normalisation process to be implemented. The equivalent mean CIELAB space model for the leaves is illustrated in Fig. 176. Again the remaining LAB models for the tree and plant species outlined in section 3.2 can be found in Appendix D.

Fig. 175 - Cubic extrapolation of mean normalized RGB values of messmate eucalypt leaves at various temperatures. Also included is a colour bar showing the normalized RGB model.
Using the two different colour models, four colour matching methods have been explored to correlate the colour of an ash particle to its average exposed temperature. Four matching methods, two within RGB space and two within LAB space, have been examined. These four matching methods were chosen as they all provide slightly different ways of correlating colours. If the colour models are well correlated to those colours of natural ash then all four matching methods should produce very similar probability distribution functions.

The first of the RGB matching methods to be examined is a sum of absolute difference (SAD) scheme. The SAD scheme is implemented using Eqn. (89). Here, the difference between each colour channel and the measured colour model is taken and these are summed. The lowest corresponding value represents the best colour match. The second RGB matching method is a ΔI method. This is a Euclidean vector based scheme whereby each channel value represents a 3D vector in colour space. In similar fashion to the SAD scheme, the minimum value represents the best colour match. This scheme is implemented using Eqn. (91). The equivalent matching error for both RGB matching methods are given by Eqn. (90) and Eqn. (92) respectively.

Fig. 176 – Equivalent average CIELAB values of the messmate eucalypt leaves at various temperatures.
\[ I_{SAD} = \sum |\Delta I_{rgb}^*| \]  

(89)

where:
- \( \Delta I_{r}^* = R_{measures} - R_{model} \)
- \( \Delta I_{g}^* = G_{measures} - G_{model} \)
- \( \Delta I_{b}^* = B_{measures} - B_{model} \)

\[ I_{error} = \frac{I_{SAD}}{\sum |\Delta I_{max}^*|} \]  

(90)

where: \( \sum |\Delta I_{rgb}^*| = 765 \)

\[ \Delta I_{rgb} = \sqrt{\Delta I_{r}^2 + \Delta I_{g}^2 + \Delta I_{b}^2} \]  

(91)

where:
- \( \Delta I_{r} = R_{measures} - R_{model} \)
- \( \Delta I_{g} = G_{measures} - G_{model} \)
- \( \Delta I_{b} = B_{measures} - B_{model} \)

\[ \Delta I_{error} = \frac{\Delta I_{rgb}}{\Delta I_{max}} \]  

(92)

where:
- \( \Delta I_{max} = \sqrt{\Delta I_{r_{max}}^2 + \Delta I_{g_{max}}^2 + \Delta I_{b_{max}}^2} \)
  - \( \Delta I_{r_{max}} = 255 \)
  - \( \Delta I_{g_{max}} = 255 \)
  - \( \Delta I_{b_{max}} = 255 \)

The first of the LAB based matching methods is called \( \Delta E \). It is identical to the Euclidean vector system implemented in the second RGB matching technique. Here, however the RGB values are replaced with the LAB values using Eqn. (93). The second LAB scheme is that using a matching scheme created by CIE called CIEDE2000 [191]. This is again a Euclidean vector which contains an extra dimensional parameter. Here, the vector magnitude is
determined by taking into consideration such parameters as Lightness, Chroma, Hue and Hue Rotation as expressed in Eqn. (95). The equivalent error for both LAB matching methods are given by Eqn. (94) and Eqn. (96) respectively.

\[
\Delta E_{lab} = \sqrt{\Delta L^2 + \Delta A^2 + \Delta B^2}
\]

where:-
\[
\Delta L = L_{\text{measures}} - L_{\text{model}} \\
\Delta A = A_{\text{measures}} - A_{\text{model}} \\
\Delta B = B_{\text{measures}} - B_{\text{model}}
\]

\[
\Delta E_{error} = \Delta E_{lab}
\]

(93)

\[
\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right) + \left(\frac{\Delta C'}{K_C S_C}\right) + \left(\frac{\Delta H'}{K_H S_H}\right) + R_T \left(\frac{\Delta C'}{K_C S_C}\right) \left(\frac{\Delta H'}{K_H S_H}\right)}
\]

(95)

where:-
- L is the Lightness (see [191])
- C is the Chroma (see [191])
- H is the Hue (see [191])
- T is the Hue Rotation (see [191])
- \(K_L, K_C, K_H = 1\) (see [191])

\[
\Delta E^*_{00\text{error}} = \Delta E^*_{00}
\]

(96)

D. Normalised Mean RGB and LAB models

A full set of RGB and LAB models for all the plant and tree species to be analysed within this dissertation can be found within this appendix. Provided is both a tabular version of the measured RGB and equivalent LAB values for each temperature range measured. Note that some species have been measured at different temperature ranges from those specified in chapter 3. This was required to better resolve the transition point towards the ember phase.
Eucalypt Genus

Messmate Eucalypt (*Eucalyptus obliqua*)

Table 22: Measured Normalized mean RGB and LAB values for *Eucalyptus obliqua*

<table>
<thead>
<tr>
<th>Temperature</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>L</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>un-burnt (22°C)</td>
<td>159</td>
<td>159</td>
<td>120</td>
<td>82.56</td>
<td>-4.47</td>
<td>12.37</td>
</tr>
<tr>
<td>150°C</td>
<td>171</td>
<td>149</td>
<td>117</td>
<td>81.41</td>
<td>1.03</td>
<td>11.79</td>
</tr>
<tr>
<td>200°C</td>
<td>186</td>
<td>130</td>
<td>115</td>
<td>79.20</td>
<td>10.00</td>
<td>9.35</td>
</tr>
<tr>
<td>250°C</td>
<td>168</td>
<td>132</td>
<td>139</td>
<td>78.94</td>
<td>8.50</td>
<td>0.49</td>
</tr>
<tr>
<td>300°C</td>
<td>162</td>
<td>131</td>
<td>146</td>
<td>78.68</td>
<td>8.45</td>
<td>-2.48</td>
</tr>
<tr>
<td>350°C</td>
<td>158</td>
<td>132</td>
<td>149</td>
<td>78.76</td>
<td>7.54</td>
<td>-3.36</td>
</tr>
<tr>
<td>400°C</td>
<td>154</td>
<td>135</td>
<td>151</td>
<td>79.08</td>
<td>5.61</td>
<td>-3.44</td>
</tr>
<tr>
<td>450°C</td>
<td>150</td>
<td>143</td>
<td>150</td>
<td>80.19</td>
<td>2.13</td>
<td>-1.32</td>
</tr>
<tr>
<td>500°C</td>
<td>149</td>
<td>145</td>
<td>146</td>
<td>80.32</td>
<td>0.76</td>
<td>0.04</td>
</tr>
<tr>
<td>550°C</td>
<td>148</td>
<td>146</td>
<td>146</td>
<td>80.43</td>
<td>0.50</td>
<td>0.18</td>
</tr>
<tr>
<td>600°C</td>
<td>148</td>
<td>147</td>
<td>147</td>
<td>80.62</td>
<td>0.17</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Fig. 177 – Cubic extrapolation of mean normalized RGB values of messmate eucalypt leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures.
Fig. 178 – Equivalent average CIELAB values of the messmate eucalypt leaves at various temperatures.

Red Ironbark (Eucalyptus tricarpa)

Table 23 : Measured Normalized mean RGB and LAB values for Eucalyptus tricarpa

<table>
<thead>
<tr>
<th>Temperature</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>L</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>un-burnt (22°C)</td>
<td>158</td>
<td>161</td>
<td>118</td>
<td>82.79</td>
<td>-5.37</td>
<td>13.25</td>
</tr>
<tr>
<td>150°C</td>
<td>168</td>
<td>153</td>
<td>115</td>
<td>81.98</td>
<td>-1.28</td>
<td>13.28</td>
</tr>
<tr>
<td>200°C</td>
<td>190</td>
<td>122</td>
<td>118</td>
<td>78.07</td>
<td>14.04</td>
<td>6.92</td>
</tr>
<tr>
<td>250°C</td>
<td>166</td>
<td>130</td>
<td>144</td>
<td>78.62</td>
<td>9.23</td>
<td>-1.63</td>
</tr>
<tr>
<td>300°C</td>
<td>161</td>
<td>131</td>
<td>148</td>
<td>78.64</td>
<td>8.45</td>
<td>-2.98</td>
</tr>
<tr>
<td>350°C</td>
<td>158</td>
<td>132</td>
<td>150</td>
<td>78.72</td>
<td>7.67</td>
<td>-3.58</td>
</tr>
<tr>
<td>400°C</td>
<td>155</td>
<td>135</td>
<td>151</td>
<td>79.02</td>
<td>6.13</td>
<td>-3.50</td>
</tr>
<tr>
<td>450°C</td>
<td>154</td>
<td>144</td>
<td>145</td>
<td>80.38</td>
<td>2.23</td>
<td>0.43</td>
</tr>
<tr>
<td>500°C</td>
<td>154</td>
<td>142</td>
<td>145</td>
<td>80.03</td>
<td>2.86</td>
<td>0.02</td>
</tr>
<tr>
<td>550°C</td>
<td>155</td>
<td>143</td>
<td>144</td>
<td>80.17</td>
<td>2.77</td>
<td>0.38</td>
</tr>
<tr>
<td>600°C</td>
<td>154</td>
<td>142</td>
<td>145</td>
<td>80.02</td>
<td>3.02</td>
<td>-0.14</td>
</tr>
</tbody>
</table>
Appendix

Fig. 179 – Cubic extrapolation of mean normalized RGB values of red ironbark eucalypt leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures.

Fig. 180 – Equivalent average CIELAB values of the red ironbark eucalypt leaves at various temperatures.
### Table 24: Measured Normalized mean RGB and LAB values for Eucalyptus tricarpa

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>L</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>un-burnt (22°C)</td>
<td>162</td>
<td>156</td>
<td>120</td>
<td>82.24</td>
<td>-2.93</td>
<td>11.96</td>
</tr>
<tr>
<td>150°C</td>
<td>170</td>
<td>149</td>
<td>118</td>
<td>81.38</td>
<td>1.05</td>
<td>11.28</td>
</tr>
<tr>
<td>200°C</td>
<td>183</td>
<td>134</td>
<td>116</td>
<td>79.68</td>
<td>8.15</td>
<td>9.61</td>
</tr>
<tr>
<td>250°C</td>
<td>173</td>
<td>130</td>
<td>134</td>
<td>78.79</td>
<td>9.79</td>
<td>1.92</td>
</tr>
<tr>
<td>300°C</td>
<td>162</td>
<td>131</td>
<td>146</td>
<td>78.73</td>
<td>8.22</td>
<td>-2.27</td>
</tr>
<tr>
<td>350°C</td>
<td>158</td>
<td>133</td>
<td>149</td>
<td>78.81</td>
<td>7.10</td>
<td>-3.17</td>
</tr>
<tr>
<td>400°C</td>
<td>155</td>
<td>134</td>
<td>150</td>
<td>78.94</td>
<td>6.31</td>
<td>-3.34</td>
</tr>
<tr>
<td>450°C</td>
<td>156</td>
<td>142</td>
<td>142</td>
<td>80.17</td>
<td>2.96</td>
<td>1.01</td>
</tr>
<tr>
<td>500°C</td>
<td>153</td>
<td>143</td>
<td>144</td>
<td>80.09</td>
<td>2.42</td>
<td>0.22</td>
</tr>
<tr>
<td>550°C</td>
<td>154</td>
<td>144</td>
<td>143</td>
<td>80.29</td>
<td>2.18</td>
<td>0.84</td>
</tr>
<tr>
<td>600°C</td>
<td>154</td>
<td>144</td>
<td>143</td>
<td>80.31</td>
<td>2.14</td>
<td>0.96</td>
</tr>
</tbody>
</table>

**Fig. 181** – Cubic extrapolation of mean normalized RGB values of spotted gum eucalypt leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures.
Fig. 182 – Equivalent average CIELAB values of the spotted gum eucalypt leaves at various temperatures.

**Acacia Genus**

Blackwood Wattle (Acacia melanoxylon)

*Table 25: Measured Normalized mean RGB and LAB values for Acacia melanoxylon*

<table>
<thead>
<tr>
<th>Temperature</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>L</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>un-burnt (22°C)</td>
<td>165</td>
<td>160</td>
<td>110</td>
<td>82.73</td>
<td>-4.29</td>
<td>16.09</td>
</tr>
<tr>
<td>150°C</td>
<td>174</td>
<td>149</td>
<td>110</td>
<td>81.57</td>
<td>0.83</td>
<td>14.81</td>
</tr>
<tr>
<td>200°C</td>
<td>182</td>
<td>128</td>
<td>123</td>
<td>78.86</td>
<td>10.66</td>
<td>6.18</td>
</tr>
<tr>
<td>250°C</td>
<td>166</td>
<td>131</td>
<td>141</td>
<td>78.88</td>
<td>8.48</td>
<td>-0.27</td>
</tr>
<tr>
<td>300°C</td>
<td>161</td>
<td>131</td>
<td>147</td>
<td>78.71</td>
<td>8.21</td>
<td>-2.45</td>
</tr>
<tr>
<td>350°C</td>
<td>157</td>
<td>132</td>
<td>149</td>
<td>78.72</td>
<td>7.18</td>
<td>-3.37</td>
</tr>
<tr>
<td>400°C</td>
<td>154</td>
<td>132</td>
<td>150</td>
<td>79.22</td>
<td>5.31</td>
<td>-2.88</td>
</tr>
<tr>
<td>450°C</td>
<td>154</td>
<td>139</td>
<td>144</td>
<td>79.55</td>
<td>3.98</td>
<td>-0.51</td>
</tr>
<tr>
<td>500°C</td>
<td>151</td>
<td>137</td>
<td>143</td>
<td>79.11</td>
<td>3.49</td>
<td>-0.67</td>
</tr>
<tr>
<td>550°C</td>
<td>148</td>
<td>136</td>
<td>142</td>
<td>78.79</td>
<td>3.01</td>
<td>-0.83</td>
</tr>
<tr>
<td>600°C</td>
<td>148</td>
<td>136</td>
<td>141</td>
<td>78.71</td>
<td>3.05</td>
<td>-0.61</td>
</tr>
</tbody>
</table>
Fig. 183 – Cubic extrapolation of mean normalized RGB values of blackwood wattle leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures.

Fig. 184 – Equivalent average CIELAB values of the blackwood wattle leaves at various temperatures.
Pteridium Genus

Austral Bracken Fern (Pteridium esculentum)

Table 26: Measured Normalized mean RGB and LAB values for Pteridium esculentum

<table>
<thead>
<tr>
<th>Temperature</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>L</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>un-burnt (22°C)</td>
<td>166</td>
<td>148</td>
<td>124</td>
<td>81.24</td>
<td>1.12</td>
<td>8.90</td>
</tr>
<tr>
<td>150°C</td>
<td>179</td>
<td>143</td>
<td>111</td>
<td>80.80</td>
<td>4.00</td>
<td>13.29</td>
</tr>
<tr>
<td>200°C</td>
<td>178</td>
<td>124</td>
<td>132</td>
<td>78.10</td>
<td>12.57</td>
<td>1.61</td>
</tr>
<tr>
<td>250°C</td>
<td>168</td>
<td>127</td>
<td>142</td>
<td>78.29</td>
<td>10.45</td>
<td>-1.67</td>
</tr>
<tr>
<td>300°C</td>
<td>158</td>
<td>131</td>
<td>149</td>
<td>78.54</td>
<td>8.00</td>
<td>-3.61</td>
</tr>
<tr>
<td>350°C</td>
<td>155</td>
<td>132</td>
<td>150</td>
<td>78.52</td>
<td>7.02</td>
<td>-3.96</td>
</tr>
<tr>
<td>400°C</td>
<td>154</td>
<td>132</td>
<td>149</td>
<td>78.55</td>
<td>6.69</td>
<td>-3.67</td>
</tr>
<tr>
<td>450°C</td>
<td>155</td>
<td>137</td>
<td>149</td>
<td>79.31</td>
<td>5.21</td>
<td>-2.43</td>
</tr>
<tr>
<td>500°C</td>
<td>156</td>
<td>139</td>
<td>146</td>
<td>79.66</td>
<td>4.35</td>
<td>-0.92</td>
</tr>
<tr>
<td>550°C</td>
<td>158</td>
<td>136</td>
<td>146</td>
<td>79.30</td>
<td>5.82</td>
<td>-1.40</td>
</tr>
<tr>
<td>600°C</td>
<td>158</td>
<td>141</td>
<td>142</td>
<td>80.00</td>
<td>3.68</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Fig. 185 – Cubic extrapolation of mean normalized RGB values of Austral Bracken Fern leaves at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures.
Fig. 186 – Equivalent average CIELAB values of the Austral Bracken Fern leaves at various temperatures.

**Pinus Genus**

Radiata Pine (Pinus Radiata)

Table 27: Measured Normalized mean RGB and LAB values for Pinus Radiata

<table>
<thead>
<tr>
<th>Temperature</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>L</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>un-burnt (22°C)</td>
<td>160</td>
<td>151</td>
<td>128</td>
<td>81.53</td>
<td>-0.84</td>
<td>7.85</td>
</tr>
<tr>
<td>150°C</td>
<td>169</td>
<td>147</td>
<td>121</td>
<td>81.14</td>
<td>1.82</td>
<td>9.77</td>
</tr>
<tr>
<td>200°C</td>
<td>181</td>
<td>127</td>
<td>127</td>
<td>78.62</td>
<td>11.38</td>
<td>4.32</td>
</tr>
<tr>
<td>250°C</td>
<td>160</td>
<td>130</td>
<td>150</td>
<td>78.40</td>
<td>8.80</td>
<td>-4.15</td>
</tr>
<tr>
<td>300°C</td>
<td>157</td>
<td>131</td>
<td>152</td>
<td>78.58</td>
<td>7.77</td>
<td>-4.31</td>
</tr>
<tr>
<td>350°C</td>
<td>156</td>
<td>132</td>
<td>152</td>
<td>78.62</td>
<td>7.52</td>
<td>-4.33</td>
</tr>
<tr>
<td>400°C</td>
<td>155</td>
<td>133</td>
<td>150</td>
<td>78.74</td>
<td>6.60</td>
<td>-3.45</td>
</tr>
<tr>
<td>450°C</td>
<td>154</td>
<td>134</td>
<td>153</td>
<td>78.86</td>
<td>6.42</td>
<td>-4.34</td>
</tr>
<tr>
<td>500°C</td>
<td>157</td>
<td>133</td>
<td>150</td>
<td>78.91</td>
<td>6.90</td>
<td>-3.15</td>
</tr>
<tr>
<td>510°C</td>
<td>155</td>
<td>144</td>
<td>142</td>
<td>80.40</td>
<td>1.93</td>
<td>1.42</td>
</tr>
<tr>
<td>550°C</td>
<td>157</td>
<td>143</td>
<td>141</td>
<td>80.30</td>
<td>2.61</td>
<td>1.71</td>
</tr>
<tr>
<td>560°C</td>
<td>160</td>
<td>140</td>
<td>141</td>
<td>79.89</td>
<td>4.25</td>
<td>1.26</td>
</tr>
<tr>
<td>600°C</td>
<td>160</td>
<td>151</td>
<td>128</td>
<td>81.53</td>
<td>-0.84</td>
<td>7.85</td>
</tr>
</tbody>
</table>
Fig. 187 – Cubic extrapolation of mean normalized RGB values of radiata pine needles at various temperatures. Also included is equivalent colour bar showing the normalized RGB model as it transitions between different temperatures.

Fig. 188 – Equivalent average CIELAB values of radiata pine needles at various temperatures.
E. Codes

Image Normalisation Macro for ImageJ

// RMIT University
// Image Normalisation Macro - ImageJ
// Created by:- Thomas Baum
// Date:- 12-June-2011
// Version:- 1.01

// Find Image Dimension (h,w)
int h = getHeight();
int w = getWidth();
    for (int x=0; x<w; x++)
        for (int y=0; y<h; y++) {
            // convert binary to RGB values (0-255)
            int v = getPixel(x, y);
            int r = (v>>16)&255;
            int g = (v>>8)&255;
            int b = v&255;

            // Process Red Channel
            if (r == 255)
                rni = 255;
            else
                rni = r/sqrt(r*r+g*g+b*b)*255;
            int rn = round(rni);

            // Process Green Channel
            if (g == 255)
                gni = 255;
            else
                gni = g/sqrt(r*r+g*g+b*b)*255;
            int gn = round(gni);

            // Process Blue Channel
            if (b == 255)
                bni = 255;
            else
                bni = b/sqrt(r*r+g*g+b*b)*255;
            int bn = round(bni);

            // Overwrite existing image data with norm data
            setPixel(x, y, (rn<<16)+(gn<<8)+bn);
        }
REFERENCES


References


References


References


[93] K. M. Mphale, "Radiowave Propagation measurements and predictions in bushfires," School of Mathematical and Physical Sciences, University of Botswana/ James Cook University, 2008.


References


References


