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Measuring the Complex Dielectric Properties of Forest Fire Ash at Various Temperatures

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***Abstract* — Little is currently known about the effects of microwave scattering on forest fires. A small number of published papers have illustrated significant return signals form large fires around the world. One of the possible sources is particulate scatter, however; little is known about their complex dielectric properties. The investigation of the complex dielectric properties from different Australian forest flora has been presented over a range of different combustion temperatures. The dielectric properties are an important step in characterizing radar scatter in order to solve an inverse scattering model. This builds on previously published work regarding the complex dielectric properties of five different flora samples over X-band frequencies. The approach to solve these complex dielectric properties is to use a Nicholson-Ross-Weir transmission/reflection method within a waveguide. The results take into account the effective volume fractions of the particles (solid/air ratio), as well as the dielectric variation caused by temperature.**

***Index Terms* — Radar, Inverse Scattering Problems, Remote Sensing, Forest Fires, Wild Fires, Australian Flora**

I. Introduction

Remote sensing of the atmosphere is a complex and dynamic field of research. The characterisation of radar scattering effects from various targets of interest falls into the field of solving what is known as the inverse scattering problem. Microwave-based technologies (including radar) are seen by some as an alternative method to detect fires over large distances [1]. These systems are alternative to currently utilised optical and infrared (IR) based remote sensing systems. To further support the argument for research into this area there have been a number of papers referencing the detection of fire plumes from ground-based weather surveillance radars [3-15].

Beyond the knowledge that radars can detect a fire plume, little is known about the sources of scatter and the meaning of these scattered signals. The main obstacle to overcome in understanding the inverse scattering problem for forest fires is the atmospheric complex dielectric constant. Significant changes will cause a detectable return signal, however; the question arises as to how early radar systems can be utilised to detect fires. The earliest stage of propagation is the surface area the fire has managed to burn before detection is confirmed. Secondly, one must understand what causes the change in the atmospheric dielectric constant. The likely detection medium is smoke, as complex terrain may not always allow for direct line of sight from a remote sensing station to the flames.

Within a plume there are a number of different scattering sources. These include solid particulates, water vapour, turbulent airflow and heat energy. By removing the solid particulate from the equation, the definitions of water vapour, turbulent flow and heat energy created from a rise in temperature can all found for in existing dielectric and scattering models. The effects of humidity, pressure and temperature can be approximated using Levy's [16] thermodynamic model (Eqn 1.).

$$\varepsilon_r = 1 + \frac{155.2*10^{-6}}{T}.p + \frac{0.746}{T^2}.e_h \qquad (1)$$

where

T = Air Temperature (K)
p = Air Pressure (millibar)
e_h= Vapour Pressure (millibar)

The scattering effects of turbulent wind can be accounted for using turbulence scattering models such as coherent Bragg scattering [17-18]. The reflectivity (η) to the radar is defined by Eqn. 2.

$$\eta(\lambda) = 0.38C_n^2.\lambda^{-1/3} \qquad (2)$$

where

C_n = Structural Constant
λ = Wavelength

Although these areas are well defined by existing models, their exact physical relation to fires requires further research. The final scattering source which is to be considered in this paper is the particulate scatter. The particulate scatter contributes significantly to the scattering characteristics of a fire plume. The ability to detect particulate scatter has been confirmed within the examined literature [7, 14]. Using polarimetric radar reading and Lidar measurement, particulate

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scatter has been defined as needle (prolate spheroids) or disk-shaped (oblate spheroids) in character.

To better understand the scattering characteristics of ash, an in-depth study of their complex dielectric properties is required. A recently published paper by Baum [19] examined the complex dielectric properties of different forest fire that were created from fires of similar temperatures. These results represent an equivalent average complex dielectric constant for the five samples measured. As the collected samples were turned into a powder, a mixing law was required to define a dielectric model. Beyond this, the final missing factor was to determine the actual dielectric of an individual particle based on its own volume fraction. This was required as the particles are largely porous [19]. Measuring the actual volume fraction of a single particle is extremely difficult. They are extremely delicate, have a very low mass requiring high resolution scales and they don't naturally conform to standard geometric shape, thus requiring some method to accurately determine their volume. The aim of this paper is to further investigate how the complex dielectric properties of fire ash alter by temperature. Using an alternative method the samples can be easily prepared and do not require the knowledge of the volume fraction.

Traditionally, measuring the complex dielectric properties in a waveguide transmission line employs the well-known Nicolson-Ross-Weir (NRW) method [20-21]. However, a primary assumption in calculating the dielectric properties of the material under test (MUT) is that it fills the entire waveguide face. It also required the MUT to be perfectly flat with a uniformed thickness. As it is difficult to create an ash particle to conform to these requirements, an alternative method was required. To solve this, a combined measurement-simulation technique was utilised, known as an optimisation approach [22-24]. It is based on an inverse scattering problem where a set of known values can be used to establish the dielectric properties of MUT. The measurement was carried out using a two-port waveguide transmission line method.

II. Samples, Test Fixture and Calibration

A waveguide test fixture has been selected for measuring the complex dielectric properties of the ash samples. The presented ash samples are leaves from a native Australian Messmate eucalypt tree (Eucalyptus Obliqua). This species has been selected as it is common over most parts of central and south-eastern Australia. It is commonly found on shallow sloping hills with sandy soils typical to the terrain found in both Victoria and New South Wales [25]. The leaves of the tree have been used for two reasons: Firstly, they have a relatively large surface area required for the photosynthesis process. This also makes them the most susceptible to fire damage and the largest contributor to solid particulates in fire plumes. Secondly, the Australian Eucalypt species has a flat, board leaf structure. This makes creating samples with geometrically defined volumes much simpler.

A. Samples

The Eucalypt samples were collected between the Angahook state park and Otways national park in south-western Victoria. The collection area is geographically illustrated in Fig 1. The leaves were left to dry naturally over 10 days at a constant room temperature (21.00°C±1.00°C).

Fig. 1. Map of the collection area found between the Angahook state park and Otways national park.

Once the samples were dried, individual leaves were taken, weighed, measured and digitally scanned to record any changes before and after they were exposed to higher temperatures. The leaf samples were then taken and placed on a hotplate. The temperatures were measured with a k-type thermocouple to improve temperature control. The Thermocouple is accurate to ±1°C. The selected temperatures were room temperature (21°C), 150°C and then 150°C to 400°C in 50°C increments. The samples were exposed to these temperatures for approximately 5 minutes, to allow them to stabilise. Once the leaves had cooled to room temperature, they were re-measured. The normalised change in mass due to temperature is illustrated in Fig. 2.

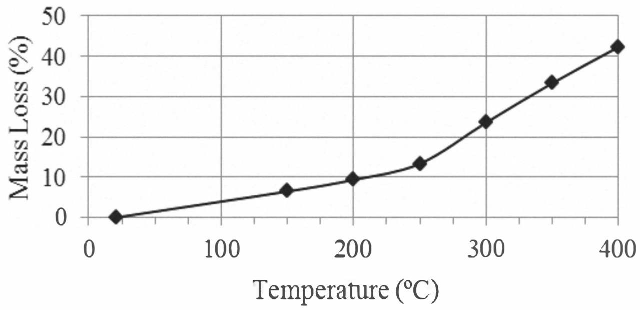

Fig. 2. Normalised change in Messmate eucalypt tree leaf mass due to change in temperature.

A visual comparison between their natural un-burnt state and burnt state is illustrated in Fig 3. Small disk samples of the specimens were then taken with an approximate diameter of 6.86mm. The varying thickness of the disks was also checked to help define their physical volume required for simulating the inverse scattering problem. A similar sized

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Fig. 3 Visual representation of the change in colour of Messmate eucalypt leaves at various temperatures

(6.80mm) disk with a diameter of 4.89mm was also prepared using Rogers 5880 substrate as calibration standards.

B. Test Fixture

The test fixture was a small 5mm section of a WR-90 waveguide transmission line (8-12GHz). The line had a small 1mm wide strip of double-sided tape adhered to the centre line of its broad sided wall. An illustration of both the Rogers 5880 substrate and Messmate samples in the test fixture are shown below in Fig. 4

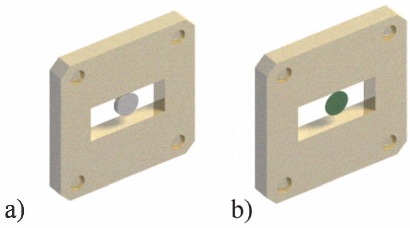

Fig 4. Example of the a) calibration standard and b) Messmate sample inside waveguide.

C. Calibration and Simulation Model

The systems must firstly be calibrated using a full 12-term Line-Reflect-Line (LRL) or Thru-Reflect-Line (TRL). The first step in determining the dielectric constant of the ash samples is to characterise a simulation model. In order to validate the simulation, the model was compared to the measurement of the two Rogers 5880 standards. In the setup, two calibration standards were measured using a vector network analyser (VNA).

There are only two S-Parameters required to find the dielectric properties, namely S_{11} and S_{21}. The phase angle can also be used as a reference, however; the magnitude is of utmost importance. The measurement is particularly sensitive to forward reflections, this being the S_{11} parameter. An illustration showing the difference between measured and simulated S-parameters magnitudes can be observed in Fig 5. The simulation was carried out using CST Microwave Studio (MWS) 2011.

Once the model had been validated, the thickness (t) and diameter of the sample was changed in the model to match that of the ash sample. The simulation was then run through the CST MWS optimisation solver.

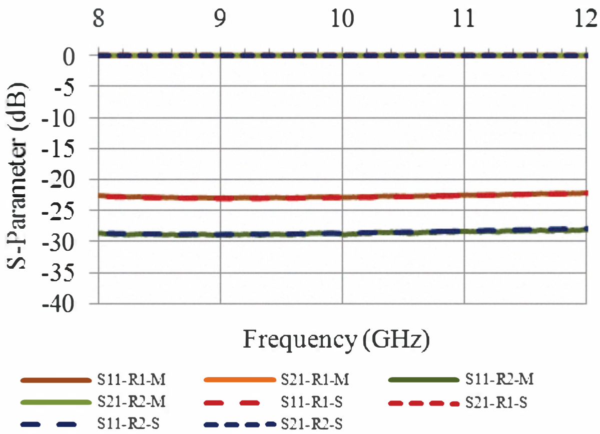

Fig. 5. Comparison between measured (M) and simulated (S) S-parameter results for the proposed test fixture. Model has been validated. R1-[Dia=6.80mm, t=1.52mm, ε=2.2, δ=0.0009], R2-[Dia=4.89mm, t=1.42mm, ε=2.2, δ=0.0009]

The optimisation regime chosen was a genetic algorithm approach. The optimisation ran a number of iterative solutions to locate the best dielectric constant and loss tangent for the given S-parameter constraints. Before starting the optimiser, it is always a good idea to know the approximate values for the dielectric and loss tangent and how these affect the S-parameters. Looking at S_{11} specifically, the dielectric constant (ε) shifts the magnitude of the S-parameter. The loss tangent is responsible for changing the average gradient of the magnitudes over the frequency band. Work by Baum *et al* [19] has also measured the average dielectric properties of different ash samples using the NRW method. This work has helped identify expected limits on the material properties required for optimisation.

III. Measurements and Simulations Results

The results from the measured S-parameters for different temperatures are illustrated in Fig. 6. The parameters optimised in CST MWS 2011. Instead of optimising 501 data points which are provided from the VNA only a few data points are required at known frequency intervals. For the

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simulation 9, 10, 11 and 12GHz have been chosen as the frequency intervals. There measured S-parameters are placed in the optimisation programs and the model is changed for the measured sample geometry. The simulation is left to run over a number of iterations with the best solution giving the approximate value for the complex dielectric constant. The resultant dielectric constant from the samples is illustrated in Table I. The dielectric model used within the simulations can then be extracted for use is other simulations such as determining the volumetric scatter or radar cross section of such particles. Finally the results can be combined with the other dielectric models (i.e air and/or turbulence). This then allows the development of a frame work to better study inverse scattering problem relating to radar scattering from forest fires.

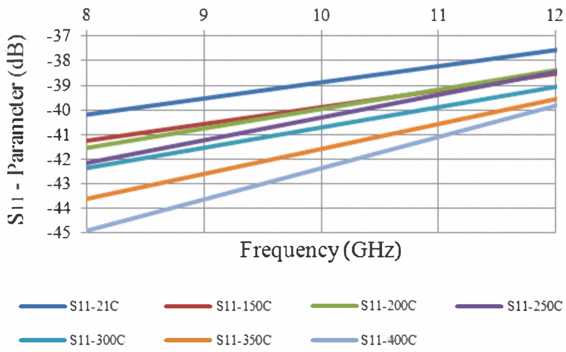

Fig. 6. Change in S-parameters of ash samples due to change in temperature over X-Band frequencies.

IV. Conclusion

Determining the complex dielectric constant from an optimisation approach has been illustrated within this paper. The effects of temperature can be seen on both the mass and dielectric constant of the ash samples. Below 250°C the rate of mass drop and dielectric constant is minimal however beyond 250°C the effective dielectric and mass reduces significantly. This is also illustrated by drop in magnitude in the S-parameters. It is unclear at this stage weather or not the reduction in mass is the sole resultant for the drop in the dielectric constant. There is also a possibility that the change in surface texture and chemical composition have a small effect on the dielectric constant. If the dielectric constant is reliant directly on the mass of the samples, it is expected it will show a similar trend to that of the normalised mass vs. temperature (see Fig. 2). This however, can only be proven with further measurements. Future work will focus on utilising the presented technique to approximate the complex dielectric constant of different ash samples. It will also focus on higher temperature measurements to around 600°C.

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