RADIO PROPAGATION IN FIRE ENVIRONMENTS

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ABSTRACT

In this paper we discuss the representation of a bushfire environment as a radio propagation medium. Basic physical models are presented to model the refractive index and combustion induced plasmas. Combustion induced plasmas will particularly focus on chemi-ionisation and thermal ionisation for electron generation. Numerical schemes are introduced to evaluate radio propagation in long range calculations concurrently with cold plasma mediums. A case study fire is used to present some results to compare the effect of propagation phenomena.

INTRODUCTION

Every Summer, Australia deals with the destructive presence of fire in the environment. With the introduction of radio communications, fire fighters have been able to communicate and coordinate efforts to aid in the extinguishment of bushfire. However, when using radio equipment, fire fighters have complained of communication performance being degraded in the presence of fire. This is particularly so when communicating across the fire front[1].

In the past, fire has been shown to interact with radio propagation in peculiar ways. Large scale fires in Queensland demonstrated that sub refractive conditions exist from the heating of the local atmosphere[2]. It has previously been thought refractive index changes are slight, however a cumulative effect can result over large distances. In laboratory flames strong ionisation has been observed in the combustion zone [3, 4]. Ions are known to exist in significant quantities dependent on the fuel used. Radar observations of smoke plumes have shown smoke and ash to have interesting scattering characteristics[5]. At lower frequencies the effect is thought to be small but is dependent on the fire and may be appreciable in large wooded fires. Small scale experiments undertaken in this work, concentrating on frequencies from 50MHz to 1GHz, have demonstrated that fire can have a significant effect on particular frequencies at different stages of the fires development. Such experimental work has led to a need for modelling the propagation medium of a fire environment.

This paper will focus on the development of simple models for the refractive index and combustion induced ionisation. The refractive index will be modelled using simple Lorenz-Lorentz theory of the various atmospheric gases. Ionisation will be treated as a cold plasma and modelled using the polarisation current of the medium. Scattering from combustion products will be ignored in this initial work but included in later modelling.

A modified two dimensional Finite Difference Time Domain (FDTD) method has been used to numerically evaluate the propagation characteristics. A novel approach has been used to reduce the computational workload and extend solutions of the FDTD method for long distances. Polarisation currents have been included in the algorithm to model the cold plasma medium present in regions of ionisation. The physical data of a bushfire has been taken from experiments undertaken in Jarrahdale, Western Australia. Fire Dynamics Simulator (FDS)[6] has been utilised to calculate the combustion characteristics of the fire. Based on this physical data propagation models have been extracted.

PROPAGATION MODELS

The refractive index of a gas is related to its density by the Lorenz-Lorentz relationship[7]. In a multiple gas environment the Lorenz-Lorentz relation is related to the sum of each individual gas[8].

$$L = \sum_i (\rho_i/\rho_{is}) \frac{n_{is}^2 - 1}{n_{is}^2 + 2} \tag{1}$$

Where ρ_i is an individual gas density at fire conditions, ρ_{is} is the gas density at standard conditions and n_{is} is a known refractive index under standard conditions[8, 9]. Knowing the Lorenz-Lorentz relation under fire conditions, the refractive index can be calculated by (2)[8]. This technique allows one to account for changes in the atmospheric gases, nitrogen, oxygen and carbon dioxide, as they undergo combustion and extreme temperatures lying outside current experimental atmospheric data.

$$n_{LL} = \sqrt{(1+2L)/(1-L)} \tag{2}$$

Ionisation of electrons in the combustion zone can occur through two mechanisms, chemi-ionisation and thermal ionisation of low energy elements. Chemi-ionisation results from transitional charged elements being generated in the chemical process. Experimental observations of the ion concentration in laboratory flames is $\sim\ 10^{12}$ions cm^{-3} [4]. Thermal ionisation occurs from natural additives in plant life that have low ionisation energy, such as calcium, potassium and magnesium[10]. If the concentration of alkali metals in the fuel is prominent with the background effects of chemi-ionisation, then the electron population can be quite large in a localised area of combustion.

Once the electron concentration can be approximately modelled, the collision frequency needs to be considered for cold plasma modelling. Itikawa[11] has calculated the effective collision frequencies for atmospheric gases at various temperatures. Under standard atmospheric conditions at ground level the collision frequency is extremely high $\sim 10^{11} sec^{-1}$. This results in a high electron population, which is heavily damped.

NUMERICAL MODELLING

Selection of a propagation algorithm is based on assumptions or limitations that can be made upon the propagation medium. Here we have taken a very general approach and desire a full solution of Maxwell's equations. Although this is computationally expensive, it is beneficial; it limits accuracy to our propagation models and not their numerical evaluation. Furthermore, by exploring only low altitudes and low frequencies (<1GHz) this aids in the feasibility of selecting Finite Difference Time Domain. That said, there are limitations with FDTD that must be overcome. The Finite Difference Time Domain algorithm suffers limitations of implementing frequency dependent mediums. If one can model the medium in the time domain it is possible to evaluate the medium and propagation concurrently. Nickisch[12] presented such a solution for ionospheric plasmas, which was further extended to any linear dispersive medium by Young[13]. This involves evaluating the polarisation current of the medium. The time domain polarisation current for an isotropic cold plasma medium is described as:

$$\frac{\partial \mathbf{J}_P}{\partial t} = -\nu \mathbf{J}_P + \varepsilon_0 \omega_P^2 \mathbf{E} \tag{3}$$

Where ν is the collision frequency, ω_P the plasma frequency and $J_P = \partial \mathbf{P}/\partial t$. The temporal-differential electric field equation is now updated to (4).

$$\frac{\varepsilon \partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{H} - \sigma \mathbf{E} - \mathbf{J}_P \tag{4}$$

A second limitation of FDTD is that very large computational grids are required for long distances. In FDTD we excite the computational grid with a pulse, which is localised in space and time. To reduce the computational workload one can truncate the computational domain to encapsulate the localised pulse as it travels through space. This results in a sliding computational window travelling with the pulse[14]. By truncating the domain we are limiting the solution; care should be taken to include transient time solutions from scattering events or mediums with long settling times. In the case of bushfire plasmas, the collision frequency or dampening term of the medium is quite large resulting in short settling times. The changes in the refractive index are known to be small and therefore strong scattering is not expected.

PRELIMINARY RESULTS

In this section we wish to present some results for the propagation models used in the numerical implementation described above. The physical data is based on a case study fire in Jarrahdale, Western Australia[15]. The simulated fire environment was assumed to be long in depth with a maximum tree height of 8 metres. A pilot fire was included to aid ignition and a $3m/s$ wind of fire spread. Fig.1 demonstrates the simple FDS object profile used and resulting averaged temperature profile from simulations. Using the output from FDS a plane wave is incident on the fire.

Refractive Index

The results of the propagation simulations are shown in Fig.2. Vertical profiles are taken at horizontal distances 30m, 70m and 120m. As can be seen the effect of the fire is very small. Sub-refractive conditions can clearly be seen as the wave energy is pushed upward for each displayed frequency. An increase in frequency shows a larger disturbance in the signal

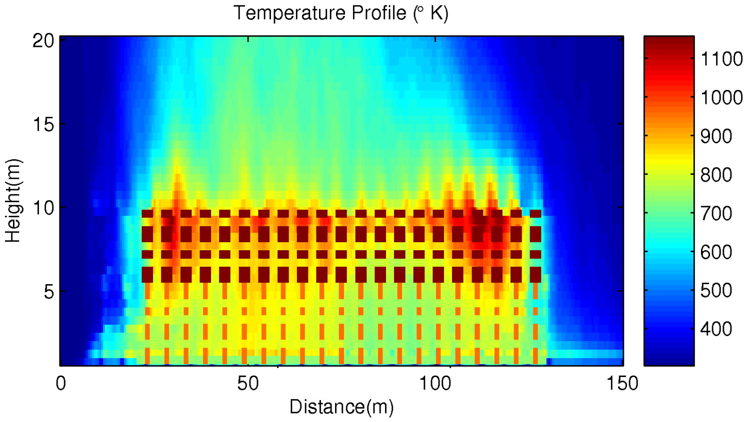

Figure 1: Fire Profile

strength. Although this effect is small over such a short distance it has been shown that the effect is accumulative over distance. Refractive effects will pose a greater problem as a longer propagation path becomes necessary.

Plasma Results

Displayed in Fig.3 is a sample of vertical profiles for different scaled maximum fire temperatures at 150MHz. The fuel loading and alkali concentrations are kept constant for each simulation. From the results a dramatic response is seen in the field strength. This effect is limited to areas of high temperature, and therefore is highly localised in space. This is particular prevalent at 70m, where the temperature profile is not as strong compared to 35m and 120m. Over long distances the plasma effect may not be as apparent but in conjunction with refractive effects the fire environment has the potential to produce some very undesirable scenarios.

CONCLUSIONS

To provide some understanding to the phenomena related to radio propagation in fire environments we have developed simple propagation models of the refractive index and combustion induced ionisation. The FDTD algorithm has been successfully modified to include the integration of cold plasma mediums with long range calculations. Results from numerical experimentation has shown that refractive effects are small but accumulate over distance and present problems in large bushfires. Ionisation present in combustion is dominant in the short distance close to the flame front. Future work includes the development of a scattering model for small particles and further investigation of propagation effects with different fire scenarios. It has been noted that more in depth experimentation focussing on particular effects is needed.

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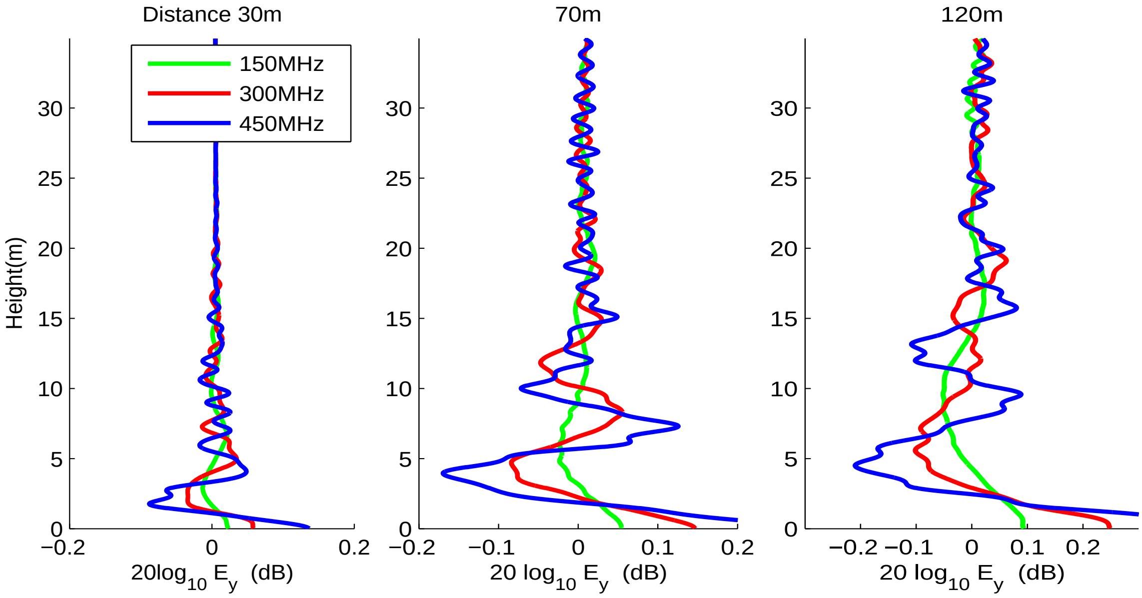

Figure 2: Refractive Index Effects

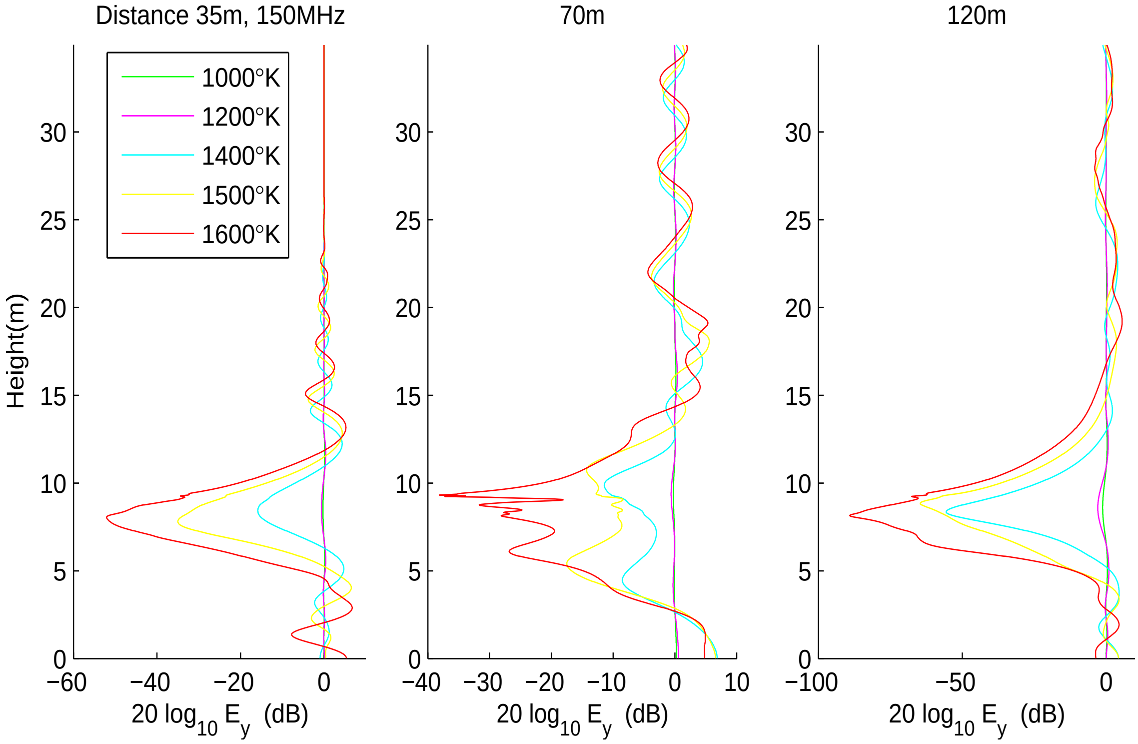

Figure 3: Combustion Plasma Effects

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