The Interaction of Lightning Impulse with *Pinaceae Pinus* (Pine Tree)

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for a degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not previously been submitted for any degree or examination to any other university.

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Megan Nicola von Poser Date

For my sweetheart, without whom I probably would have finished much sooner, but it would have been a far less exciting journey.

ABSTRACT

The work presented extends and contributes to research in lightning and *Pinacaea Pinus* (pine trees) and focuses on the initial interaction between the current impulse and the tree trunk. Although previous work in this area has produced some general hypotheses of the outcome of this interaction, no modelling has been attempted to provide estimations as to which factor might be of most importance, in particular whether or not the biological components of the tree play a major role. Resin as a specific constituent of pine is excluded as a contributor, through laboratory experimentation as the impedance is too high to allow for substantial current flow. Using computer simulations of macro-geometrical structures of water vessels, the volume of water and moisture content levels are found to be the main factors in determining the amount of resistive power loss (heat) observed in the wood material. The wood variation is modelled using twelve combinations of permittivity and conductivity and the lightning impulse is simulated using a $10\,\mathrm{k}A$ peak Heidler current waveform. The high permittivity values of the wood allow for an energy exchange to occur between the wood and water when the conductivity of the wood is not high.

ACKNOWLEDGEMENTS

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Chapter 1

Introduction

The interaction of lightning and trees encompasses multiple domains of knowledge such as plant physiology and electrical phenomenology. While this topic is broad, the specific focus of this dissertation is:

"Which component of the tree is important in determining the amount of damage sustained from a lightning attachment?"

There is a large range of outcomes in terms of damage that may occur to a tree, as summarised in the following figure:

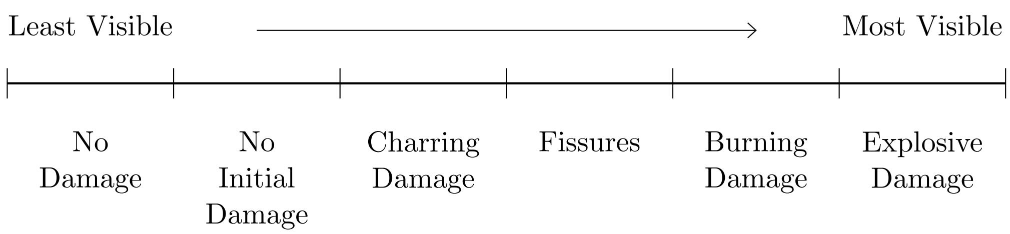
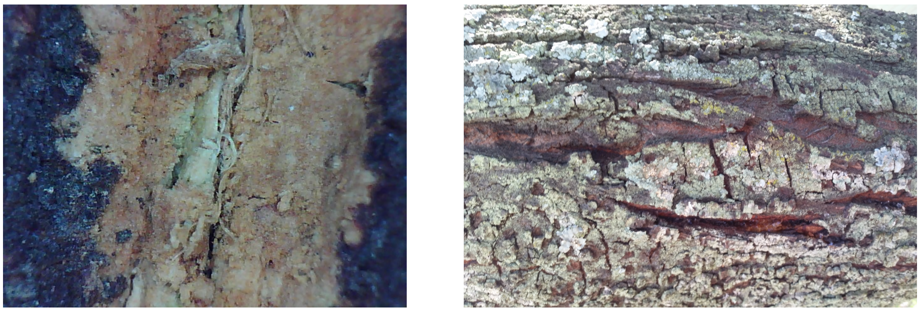


Figure 1.1: Observability of damage sustained by lightning on a tree

More general classifications of the damage have been made, but this range is more suitable for this dissertation as it is more detailed in the middle range [1, 2]. As seen above, the damage can range from the tree surviving and showing no damage to explosive damage where tree matter is ejected some distance away [3]. Special cases that have been observed include the tree showing no damage initially and then after some time has passed the tree tissue starts to decay [4]. The charring, fissures and burning damage are all similar; charring indicates that the bulk of the material remains unchanged but the small tips of the tissue fibers carbonise, while fissures indicate that there is tissue loss, often along a line and sometimes with charring, burning indicates that there has been ignition with fire burning the tree tissue to a larger extent.

Examples of the different types of damage observed on trees can be seen in *Figure 1.2*, *Figure 1.3* and *Figure 1.4*.



(a) Magnified fissure damage in tree branch

(b) Fissure damage along trunk

Figure 1.2: Example of fissure damage

In *Figure 1.2*, the fissure is clearly visible along the trunk of the *Acacia Galpinii* tree with some charring evident within the fissure. The magnified fissure damage shows the wood fibers forced outward from the body of the stem, but no charring or burning is visible, despite these being from the same tree.

Figure 1.3: Example of burning damage with location map data of possible sources for lightning attachment

Figure 1.3 shows the result and location of a lightning attachment to a palm tree. The possible current values, ranging from $-4\,\mathrm{kA}$ to $-46\,\mathrm{kA}$, can be seen in the map image as there are multiple possibilities of the lightning stroke that caused the damage. The map shows current values for strokes recorded at the approximate time and location that the event was witnessed.

The data for the lightning is from the South African weather services. The ellipses are error plots, where the yellow ellipses cover the point of interest and the centres are marked by the peak current value. It is uncertain which of the strokes is the most likely to have attached to the palm tree.

Figure 1.4: Example of explosive damage

The pine tree shown in *Figure 1.4* is an example of the explosive damage seen from a lightning interaction. While the tree showed excessive damage, there were no indications of charring or burning.

1.1 Outline of Dissertation

The dissertation will be divided into the following chapters:

Chapter 2: Some background to the research is given, first describing the lightning knowledge most often used and second introducing some of the general concepts about trees that are needed to understand the work. Some existing work in this field of research is also described.

Chapter 3: The experimental work chapter describes some experiments performed in the high voltage laboratory under impulse and DC conditions on specimens of *Pinus Elliotii* wood and resin.

Chapter 4: Several models investigating the dielectric values, geometry parameters and some other factors of the tree are presented in this chapter. The macro-geometry of trees is also compared using the same modelling technique, as well as the effects of the volume and placement of water vessels.

Chapter 5: This chapter discusses the meaning of the results of the modelling, with some links between the experimental, modelling and existing work proposed.

Chapter 6: The chapter concludes the dissertation and offers some recommendations about the work done in the models and experiments.

Appendix A: The first appendix is a paper presented at the *South African Universities Power Engineering Conference* (SAUPEC) about the literature for the modelling experiments.

Appendix B: The impulse generator circuit used in the resin experiment is presented.

Appendix C: The next appendix is a paper presented at the *International Conference on Lightning Protection* (ICLP) about the resin experiments.

Appendix D: This appendix gives more detail about how the ground terminal is modelled.

Appendix E: The currents for all combinations of permittivity and conductivity are presented here for Case B, the external water channel test.

Appendix F: This appendix summarises the test performed on the placement of the integration surface for current.

Appendix G: The currents for all combinations of permittivity and conductivity are presented here for Case C, the internal and external water channel test.

Chapter 2

Background

Overview

The following chapter describes the fundamentals of lightning pertinent to this dissertation and outlines the biology basics upon which the research is based. The relevant literature is discussed as it pertains to the interaction of lightning and impulse currents with trees.

2.1 Lightning

Lightning research is a broad field involving many disciplines each with many aspects to this phenomena, not all of which are relevant. The following section details which specific parts of the phenomena will be focused on in this dissertation.

First, a lightning flash consists of short and long strokes, often in succession [5]. The short stroke is defined as an impulse current typically less than $2\,\mathrm{m}s$ long, whereas the long stroke is a continuing current. This is illustrated in *Figure 2.1*. This research will focus on a single short stroke to examine the effect of the impulsive nature of the lightning stroke.

There are also cloud-to-cloud and cloud-to-ground types, where the cloud-to-ground can cause five different mechanisms of lightning injury: direct strike, touch voltage, side flash, step potential and upward streamers [6]. This work considers mainly the direct strike as this causes the most damage, although the interaction would be similar for a touch voltage or side flash.

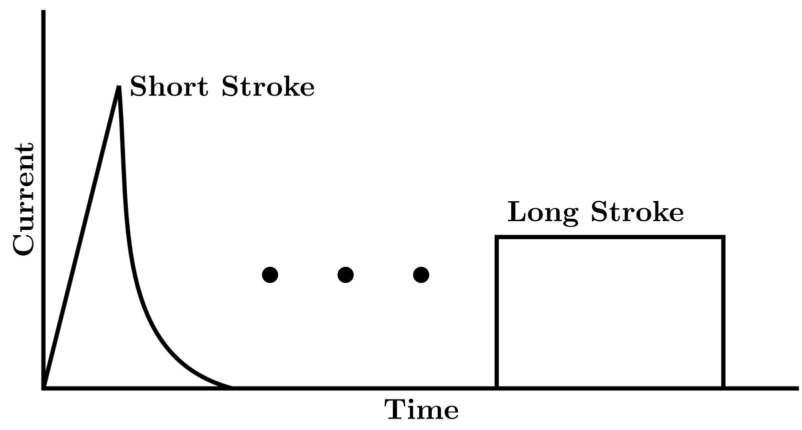


Figure 2.1: Illustration of long and short strokes in a lightning flash

Similarly, there are upward and downward types and positive and negative strokes. While the mechanisms involved in the positive and negative strokes are different (positive versus negative charge carriers) the main focus is on the current magnitude of the stroke itself [7]. The positive strokes are statistically likely to be large positive peak values, much higher than the negative strokes. However, as with all lightning, these statements are determined statistically, which does not preclude there being significantly large negative strokes [8].

A peak current magnitude in the range of the negative return strokes (10 kA to 30 kA) will be focus of the investigation because when the peak current values are high, the properties of the tree are unlikely to make any difference since there is such a large amount of energy that passes through the tissue. An exchange of current with a tissue (or between two) is equivalent to an exchange of energy.

2.2 Pine Tree

A tree is a complex living entity, of which there many different types with many different properties. The quantification and simplification of the key characteristics of a tree need to be done in order to answer the question posed for this dissertation. Choosing a specific tree limits the possible characteristics, therefore a tree species has been chosen due to the abundance in South Africa and the unique chemical composition.

The slash pine, or *Pinus Elliottii* is a coniferous tree of the family *Pinaceae* and order *Pinales*. It has needle-like leaves and reaches heights of 18 m to 30 m with a trunk radius of 0.3 m to 0.4 m. A plantation of eight year old *Pinus Elliottii* can be seen in *Figure 2.2*. The resin consists of two main components, the terpenes, largely the volatile monoterpenoids, and the gum rosin [9].

Figure 2.2: Plantation of *Pinus Elliottii*

Although choosing this specific tree reduces the complexity of simulating a natural occurrence of a direct attachment, the research performed on other tree species can still be used to gain insights into an interaction with a general tree which can then be expounded upon to the specific case of the slash pine.

The main elements of a generalised tree that will be used in the following chapters can be seen in *Figure 2.3* and *Figure 2.4.* On a macro-level the tree is divided into the crown, trunk and roots. The effect of the roots on the extent of the step potential have been investigated and found that the spreading root type extended the step potential outward [10]. The crown is not considered in this work, particularly as there are needles instead of leaves and the pine has a spiral growth pattern, not forming a large crown. The trunk is the main focus as this is where the damage is more visible.

Within a trunk or tree bole, the heartwood and sapwood describe different areas of the wood material but consist largely of the same tissues, but the heartwood is denser and has a much lower moisture content than the sapwood. The vessels within the sapwood transport water and dissolved minerals to the crown of the tree while the cambium produces new cells. The bark has a protective function, as does the resin which is specific to a few families of trees including *Pinaceae*. The resin is present in small channels throughout the tree, mainly in the direction parallel to the trunk [9].

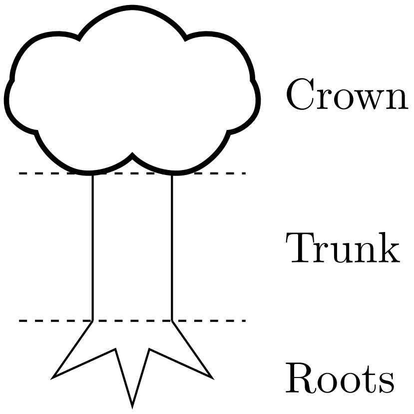


Figure 2.3: Tree regions

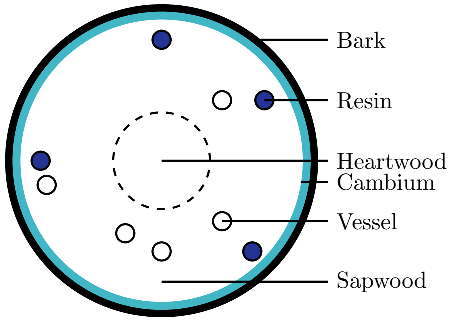


Figure 2.4: Top down view of trunk (Not to scale)

These layers are all distinct from each other, not only in their function but their structure as well. As their structure and moisture content will vary, so will the impedance.

The earliest relevant literature to consider the electrical properties of trees is a resistance measurement of a tulip tree in 1956 by *FM Defandorf* [11]. Here, the electrical resistivity of a live tree are measured under DC conditions and the salient points are catalogued:

1. The resistivity is lowest in the longitudinal direction of the tree
2. The resistivity of the living part of the tree (cambium layer) is often half the resistivity of the interior wood
3. There is a negative thermal coefficient

The first point is supported by *Daian et al* [12]. As current would likely travel the path of least resistance, this is an indication why the observed paths on a tree are from the point of attachment directly downwards to ground.

The second point indicates how the bark is likely ejected as the cambium layer is directly beneath it.

The third, while not investigated in depth, indicates that if there are multiple strokes or a second attachment at a later time, the likelihood of a flame due to the heating effect of the current is greater. As the variation of the impedance in the tree trunk tissue results in anisotropic current density, there is a filamentary concentration along paths, theoretically causing greater damage, either through destruction of the cells or burning. This effect has been observed by *Taylor* as well, as he noted that the fires in a forest of mainly *Douglas Firs*, when started by lightning attachment, were usually when it was the second occurrence of attachment to the tree [13].

On a microscopic level, fusion of quartz and microparticles has been observed on a tree from a lightning attachment, as well as carbonation, indicating very high temperatures and energy values [14].

Makela et al use case studies of various trees for which the lightning data is known to attempt to quantify common theories about lightning and trees, such as whether some trees are more susceptible to damage than others or whether the damage is proportional to the current magnitude [1]. The magnitude is found to correlate, but whether a factor of the trees physiology affects the amount of damage is not confirmed. The case for old and damaged trees exploding from lightning is found highly likely, but there are very few cases from which to conclude this.

2.3 Literature

Not within the scope of this dissertation are wood poles as used in the power distribution network. While there is literature which discusses the wood pole relationship to lightning, the wood is dry and treated and thus not the same as a live tree. However, there are some points which can be connected to a live tree interaction, mainly that the path of the current flow is either observed along the outside of the pole, or within, but never both [15]. These observations are made for laboratory simulated lightning though, which does not have the same energy capability as that of natural lightning.

For a more in depth review of the literature relating lightning and pine trees, a paper was presented at the *25th Southern African Universities Power Engineering Conference* (SAUPEC) conference in Stellenbosch; this paper can be found in **Appendix A**.

Conclusion

This chapter has discussed the background used in this dissertation. Both the tree and lightning are complex systems, so specific areas and types are chosen to reduce the scope of the research. Only smaller magnitude, short stroke attachments are considered to a *Pinus Elliottii*. The following chapter will present the laboratory work undertaken at the *University of the Witwatersrand* where the primary focus is to confirm or exclude the resin as a component affecting the interaction of lightning and pine trees.

Chapter 3

Experimental Work

Overview

This section details the initial work performed in the laboratory to investigate the effects of the interaction of lightning and pine trees. Specifically what role the resin plays, what happens when HVDC voltage is applied to the wood and what voltage is required to breakdown the wood.

3.1 Resin Tests

As described in the background chapter (**Chapter 2**) the resin of a pine tree contains terpenes which are highly flammable and have a low flash point [9]. A theory proposed initially is that the flammability of this substance is the cause for the combustion that occurs in a pine tree; however, as there was no full conduction current this can not be confirmed. As the resin showed such a high impedance, it is unlikely that it would form part of the lightning current path.

3.1.1 $8/20\,\mu s$ Impulse

To test what effect the resin has in the interaction, the resin was harvested directly from *Pinus Elliottii* and subjected to impulse tests using the $8/20\,\mu s$ impulse generator. For a circuit diagram of the generator see **Appendix B**.

The generator was used in combination mode where it applies the standard voltage waveform as described in **Chapter 2**. If breakdown occurs then a current waveform is produced as in *Figure 3.1.* While this type of current waveform is generally used to model an indirect strike, it is used in this context as the resin channels are internal to the wood material [16].

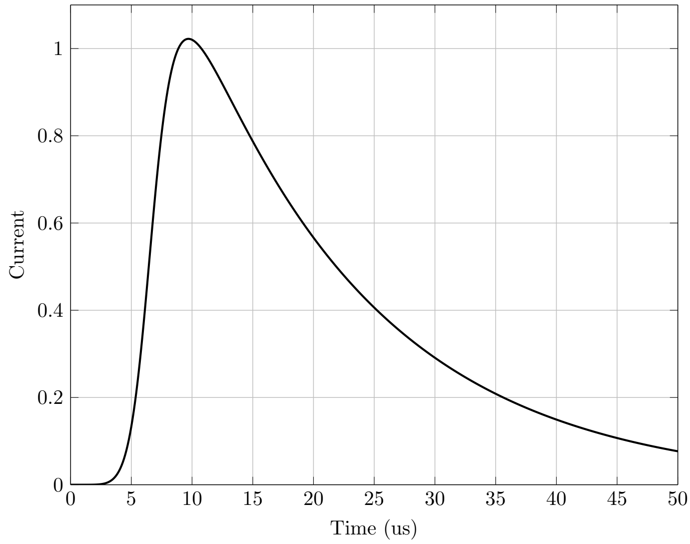
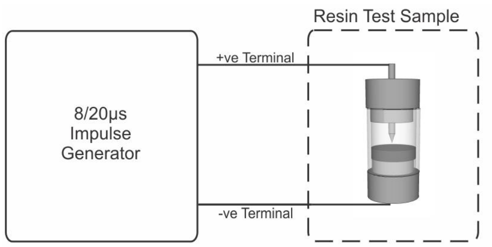
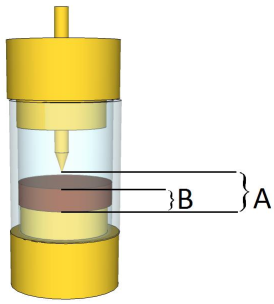


Figure 3.1: The 8/20μs current impulse

The experimental set up is described in *Figure 3.2.* An impulse voltage was applied via the positive terminal and the potential was measured across the flash gap, along with the instantaneous current. The impulses ranged from 2 kV to 18 kV peak voltage, while the flash gap was set to 2 mm and 0.5 mm, with 3 mm and 2 mm resin height respectively.



(a) Electrical connections for resin capsule with impulse generator



(b) Apparatus used to test resin (A is flash gap and B is resin height)

Figure 3.2: Experimental setup for resin test

Even with the smallest flash gap and highest peak voltage (0.5 mm - 18 kV), there was no full breakdown of the sample. This implies the resin has a very high impedance under impulse conditions, but an exact value has not been obtained.

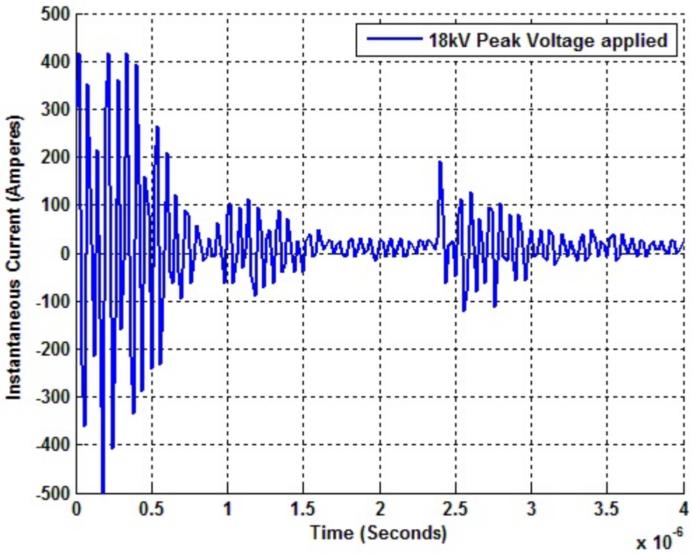


Figure 3.3: Instantaneous current on the resin sample for 18kV peak impulse voltage applied

There was some leakage current that occurred in a ringing pattern as can be seen in *Figure 3.3*. This was thought to be due to either switching artefacts from the impulse generator or a repeated vapourising of the more volatile constituents of the resin.

For a more in-depth report of the experiment as presented at the *International Conference on Lightning Protection*, see **Appendix C**.

3.1.2 DC Test

An experiment under DC conditions was also performed on the *Elliotii* resin collected in the same forest to test if the high breakdown strength would persist. However, the mechanisms that lead to breakdown are not the same for a DC test as compared to an impulse test. A continuing DC current is applied, rising linearly until a breakdown is observed. The same test capsule is used as in **Section 3.1.1** with a point to plane set-up.

With the sharp point in this set-up, the electric field is concentrated at the tip, which is submerged in the resin. The flash gap (distance from plane to tip) is 3 mm.

Corona could be heard as the voltage passed 4 kV, while a breakdown path was formed at 6 kV. The current was allowed to continue for 5 seconds at this current and a carbonisation channel formed and grew larger as the current was allowed to continue.

This continuing DC breakdown strength is much lower than the impulse breakdown strength, which is to be expected for any material, but the DC breakdown strength is still large at 6 kV for 3 mm. As this test was an informal measurement of the DC-characteristics, no waveforms were recorded, but a standard DC breakdown is probable with a continuous current. No repeat tests could be made due to the unavailability of the material and the destructive nature of the test.

Along with the distinct carbon channel, the viscosity of the sample increased noticeably after the experiment, with no movement of the liquid occurring.

3.2 Tree Tissue Tests

An impulse test was also performed using the Marx-generator to observe the breakdown voltage without the high current flow. Rogowski-profile electrodes were used with a slice of the trunk, 6 cm in diameter and 3 cm in length, placed in the longitudinal direction in between the electrodes. The sample was collected from a five year old tree near the middle of the trunk after it had been air dried in the laboratory for a year under room temperature, pressure and humidity conditions.

An impulse voltage of 30 kV was applied with no breakdown occurring and applied a second time after waiting two minutes with no true breakdown. However, upon inspection, tracking artefacts were found along the perimeter of the wood and a third application caused breakdown but was thought to have been through the tracking channel.

A U50 test, as defined in the IEC 60060-1 standard [17], cannot be followed in this case as repeated breakdowns could lower the resistivity of the wood, following the literature in **Section 2** and the breakdown occurs in the carbon channels along the perimeter and not in the wood material itself.

As the wood used in the test was dry, there is less similarity between it and a live tree. As there is little current flow, there is very little similarity between the impulse applied in a laboratory condition and the occurrence of a lightning attachment. The dry wood also has a much higher resistivity as there is less moisture, this leads to a higher voltage needed for breakdown so the significance of the species is also lost as most wood will tend towards a maximum resistance when the finer structure is lost.

Conclusion

This section has illustrated some effects of simulating lightning under laboratory conditions on wood and resin. The resin experienced no breakdown under impulse conditions up to 20 kV over 2 mm, but formed a carbon channel for DC conditions at 6 kV. The wood specimen undergoes a breakdown near 30 kV after repeated impulses from a Marx-generator, but this is likely due to tracking along the perimeter of the wood rather than through it. The path of the current and power lost can not be observed in an experimental setting and the high current and voltage requirement of a more accurate representation of a lightning attachment makes a computer simulation of the interaction more useful. The following section details the virtual experiments carried out to observe and answer questions about the details of the interaction of lightning and a tree.

Chapter 4

Modelling Work

Overview

The following chapter documents the modelling work performed such that some insight can be drawn about the current and the internal interactions that could not otherwise be obtained from experimental work in a laboratory. First, the general setup of the models is explained, such as how the geometry, sizes and dielectric values are obtained. Second, the heartwood volume simulation is detailed, followed by several tests to evaluate the effect of water channels and their placement on the tree trunk. Lastly a macro geometry test is reported which compares the *Pinacaea Pinus* growth habit to that of a bushy type growth.

These models are not intended to mimic the natural occurrence of a direct lightning attachment to a tree as closely as possible, but rather to simplify the interaction so that some inferences can be drawn. By using a multi-physics modelling software [18] multiple interdependent physics can be modelled and included.

4.1 Simulation Setup

As the magnetic effects of currents in the simulation are assumed to be insignificant as the permeability of wood is relatively low [19], only electric fields are utilised in the modelling environment to reduce computational time. Full breakdown mechanisms are not modelled, analysing only the current density and the electric field potential.

The electric potential is calculated within the modelling domain using Maxwell's equations in the weak form, as in *Equations 4.1, 4.2* and *4.3. Equation 4.1* describes the electric insulation (conservation of energy) that has to be applied to the model boundaries; The other two equations are part of the conservation of current laws. *Equation 4.2* assigns the electric field to the scalar voltage, while *Equation 4.3* is the time-dependent relation of the electric field derivative to the current density, using the properties of the materials and the existing current density (bound charge current density).

$$0 = \vec{n} \cdot \vec{J} \tag{4.1}$$

$$\vec{E} = -\Delta V \tag{4.2}$$

$$\vec{J} = (\sigma + (\epsilon_0 \epsilon_r \frac{\partial}{\partial t})\vec{E}) + \vec{J_e} \tag{4.3}$$

where:

$\vec{n}$ is the normal vector

$\vec{J}$ is the current density

$\vec{E}$ is the electric field

V is the scalar voltage potential

σ is the conductivity

$\epsilon_0 \epsilon_r$ is the permittivity

$\vec{J_e}$ is the bound charge current density

To reduce the problem of simulating a tree and lightning interaction, some simplifications have to be made to the geometry and material properties of the model. Only the tree trunk will be examined, by modelling it as a cylinder of "wood" material, except in the case where the macro-geometry of the tree is being discussed. The water channels are larger than would be natural in a tree trunk and only certain layers of the bark will be included in the model. The layers that are included will be discussed in the individual simulations for which an extra layer is present.

4.1.1 Dielectric Properties

As a tree consists of living material, there is a large range in the properties it can have. As with most materials, the dielectric properties vary with frequency and temperature. Wood dielectric properties are also largely dependent on the moisture content, as multiple publications have confirmed [12, 20, 21].

The dielectric properties needed to model a material in the electric currents domain are the electrical conductivity (η) measured in S/m (Siemens per meter) and the permittivity (ϵ). It is assumed that the applied voltage is not excessively large, so that the values taken from literature can be applied.

The conductivity indicates the materials ability to allow a conduction of current through it, the higher the conductivity, the more the material will conduct.

The permittivity of a material is an indication of the ability of the substance to store energy in an electric field. It is equal to the relative permittivity (ϵ_r) multiplied by the permittivity of free space (ϵ_0). This is because the relative permittivity can be measured as the charge stored in the material, compared to the charge that would be stored in a vacuum for the same volume.

Relative permittivity is sometimes measured with both a real value, often called the dielectric constant, and an imaginary component, often called dielectric loss. The dielectric constant represents the charge storage ability, whereas the dielectric loss quantifies the electromagnetic energy loss of the material, for example as heat.

Because of the multiple types and strata that the trunk consists of, even small blocks of wood specimens are non-homogeneous and anisotropic, which makes obtaining the dielectric values difficult, particularly in the lower range (under 100 kHz). Several factors influencing the material properties are described in the following sections, along with reasons for the the final choice of values.

Frequency

To assess which frequency range is valid for lightning impulses, the power spectral density (PSD) of the applied waveform is acquired numerically. The chosen waveform is described in detail in **Subsection 4.1.2**, but the PSD can be seen in *Figure 4.1*. It is obvious that the majority of the power is in the lower frequency range and attenuates at 20 kHz. Therefore, values for the dielectric properties will be considered only if they were obtained below this frequency range.

Moisture Content

Moisture content is an important factor determining the dielectric properties of wood [22]. This is seen in other materials as well, but as wood is naturally hygroscopic, the change in moisture content is quick. However, there is a large difference between wood that has been soaked to a certain moisture level and one that has been measured “fresh” from a tree at the same level. This is because while the moisture level, measured by the ratio of weight from wet to dry, might be the same, the ionic compounds in the specimen are different. As wood dries the volatiles evaporate

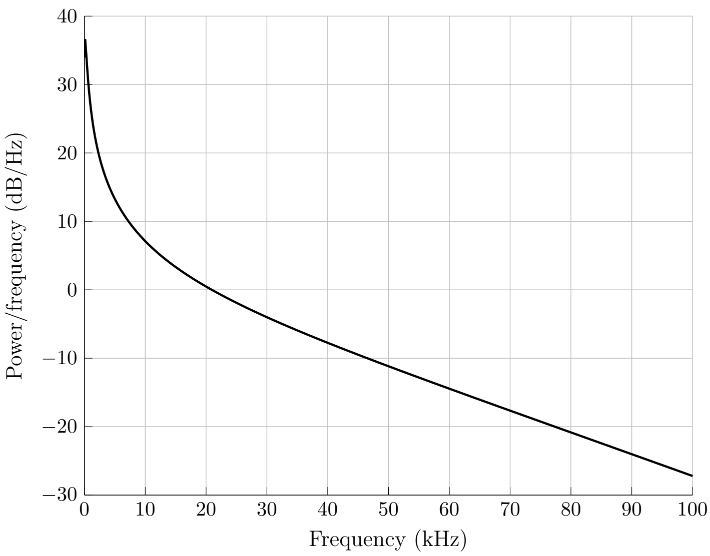


Figure 4.1: Power spectral density of short stroke current waveform ($10/350\mu s$)

along with the water and other molecules contained therein and the pits (minute openings between the vessels) collapse, altering the way in which the water is stored within the wood. These ions and molecules are then not returned to the wood when it is soaked.

When the conductivity is measured at a lower moisture level the specimen is being measured indirectly for available water, but once the level is higher, the water within the specimen is indirectly being measured for ionic content. Once the specimen has a high enough water content, usually above the fiber saturation point[1] (FSP), the ionic constituent or flow is the main factor affecting the permittivity fluctuations. These fluctuations are relatively small as the conductivity and permittivity have effectively plateaued in comparison to the steep rise from a lower moisture content [23].

As can be seen in *Figure 4.2* and *Figure 4.3*, the general behaviour of the conductivity can be indicated as inversely proportional to frequency and proportional to temperature.

At low moisture content, the permittivity and conductivity are very low, indicating insulator properties. This is to be expected as wood is often used for poles in line conductors. The problem arises when there is high humidity and the wood absorbs the moisture, causing the conductivity to increase and flashover is more likely to occur as the wood provides a path for the current to flow.

[1] The point at which there is only bound water in the fibers of the wood and no free water

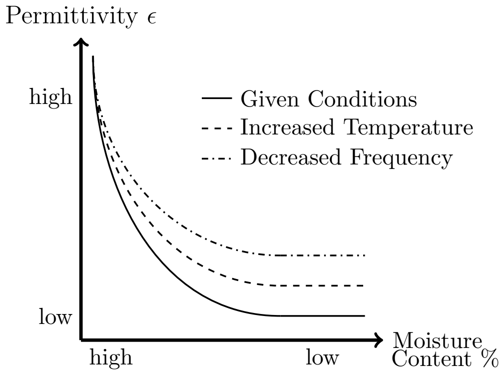


Figure 4.2: Behaviour of permittivity for a change in frequency and temperature

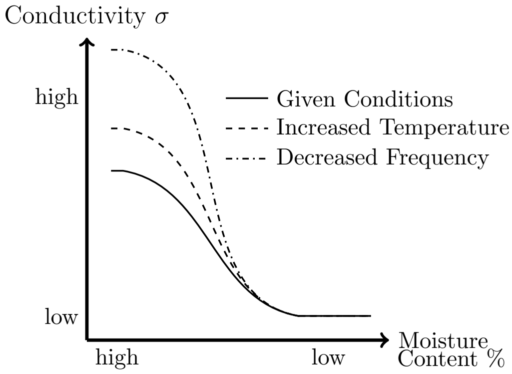


Figure 4.3: Behaviour of conductivity for a change in frequency and temperature

In the experiments as described in **Chapter 3**, the wood that was used was dry and therefore had a very low moisture content, which is why breakdown could not easily occur. However, the main objective of the experiments was to test resin, which also has a very low moisture content(2%). This substance also proved to have a very high impedance.

There is a distinct difference in moisture content between hardwoods and softwoods, as the moisture content is also linked to the density of the wood material [24, 25]. The more dense a wood is, the more lignin it contains, which makes the wood structurally stronger (hardwoods). Species with higher density have higher permittivity, which means they should store more charge. A comparison between hard- and softwoods can be seen in the values in *Table 4.1.*

The species in focus for this dissertation is the *Pinus Pinacaea*, which is a softwood and so should be closer to the *Douglas Fir*, which is in the same family as the pine *Conifers.* One notable attribute of the pine is that there is a sizeable difference between the samples drawn from the heartwood and sapwood regions [26, 27]. For this reason, a simulation is conducted in **Section 4.2**, using a lower conductivity and permittivity than used elsewhere, to emulate the heartwood.

An as yet not understood factor of coniferous trees would be the resin and what effect it would have on the dielectric measurements and the interaction with lightning. As no values could be found for the unprocessed resin compound, it is assumed that both the permittivity and conductivity are very high and low respectively, especially noting the experiments performed in the laboratory in **Chapter 3** and the fact that the material is highly viscous and has a very low moisture content [23].

As the literature does not focus on live wood, dielectric values for samples with moisture content closest to the live wood are considered, but around 100% or more are optimum.

Table 4.1: Summary of dielectric properties of wood at different frequencies and moisture values

Frequency (Hz)	Conductivity (S/m)	Dielectric Constant	Dielectric Loss	Moisture [a] Content (%)	Temperature (Celsius)	Direction [b]	Species	Publication	Notes
100 1000 10000	-	3.2k 230 45	35*3.3k 44*230 21*45	90	25	Longitudinal	Douglas Fir (Softwood)	*James* [23]	
100 1000 10000	-	53k 3.1k 307	49*53k 90*3.1k 93*307	Soaked	25	Longitudinal	Douglas Fir (Softwood)	*James*[23]	
100 1000 10000	-	1600k 680 100	29*1600k 25*680 19*100	90	25	Longitudinal	Oak (Hardwood)	*James*[23]	
100 1000 10000	-	230k 20k 2.2k	14*230k 17*20k 15 *2.2k	Soaked	25	Longitudinal	Oak (Hardwood)	*James*[23]	
100 1000 10000	-	50 - 250 20 - 100 10 - 50	60 - 700 1 - 150 1 - 10	Air Dried	30	Radial	Various	*Marella*[31]	Kadam Teak Sal
60 – 1k	1/10k–1/100	-	-	Fresh	Room Temperature	Longitudinal	Various	*Gora and Yanoviak*[32]	Stem Diameter affects Conductivity
8.3	1/2500 – 1/250	-	-	Fresh	Room Temperature	Radial	Pine (Softwood)	*Guyot* [26]	Heartwood vs Sapwood Specimens
0.001 – 1k	1/120 – 1/10 1/1200 – 1/80	-	-	Fresh Soaked	20	Radial	Various	*Martin* [33]	Fresh vs Soaked Wood Specimens

[a] Percentage weight measurement as ratio of oven dry weight
[b] Measured as grain orientation in relation to applied field

Temperature

Similarly, temperature also increases the conductivity and permittivity of the wood, but no upper limit was found in the existing literature. Temperature affects the moisture content and thus the dielectric values indirectly as well. As the temperature increases dessication occurs, lowering the moisture content and therefore lowering the dielectric properties. Through this interaction, the temperature has a smaller proportionality to the dielectric values than the moisture content [28].

As stated previously, there is a large amount of variance in the samples which is ignored to simplify the simulation. One such factor is the time at which the sample is taken, as this effects the amount of moisture in the material as the tree transpires and has a complex natural rhythm of transporting fluids [29].

The most appropriate temperature is around standard room temperature (25 °C) or close to this, as the effect of heating or freezing to higher values is being ignored. This assumes that the tree is under standard conditions when a lightning attachment occurs.

Species

The initial focus of this dissertation was on one species, the *Pinus Pinacaea* with work having been carried out on the *Pinus Elliottii*. However, as there is very little data available on the dielectric values for this specific tree species, a broader approach must be taken. From the literature seen in *Table 4.1*, for a given situation[2] there is some variation in the tree species, but the permittivity remains in the same order of magnitude even for very different types of trees (Hardwoods and Softwoods seen in the first four rows in the table).

Direction of Measurement

Wood is an anisotropic material, one reason for which the grain and growth rings form structural layers through a change in density in the tree material. When viewing along the three axes described in *Figure 4.4*, three different amounts of the denser layers will be present in the same size. As the longitudinal direction would likely have a consistent layer of denser wood, it is conceivable that it would have a higher permittivity, as mentioned about density previously. This is confirmed in the literature [28, 30]

[2] Set moisture level, frequency, temperature and direction of measurement

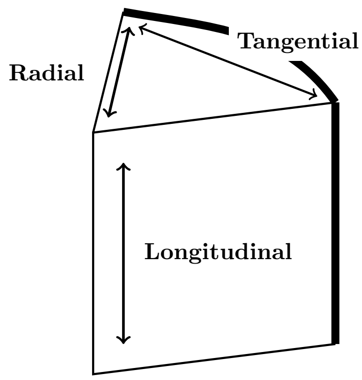


Figure 4.4: Illustration of wood direction terminology

The modelling software can not easily model a material with directional dielectric properties, thus the dielectric values that have been measured in the most appropriate direction are used. In this case, the most appropriate direction is the longitudinal, as the path of current flow is perpendicular to the ground, along the longitudinal direction.

Conductivity and Permittivity used in Model

A summary of the most relevant publications are presented in *Table 4.1.* Each factor affecting the dielectric properties has been explained above.

Following all of the aforementioned factors, the best match for the permittivity are the values measured by *James*[23] for a *Douglas Fir* in a longitudinal direction. The temperature is at the desired value, but the moisture content is only at 90%. This is considered closer to a live tree permittivity value, as the soaked measurements are likely measurements of different ion compounds and percentages, as explained previously. The range described for conductivity varies between 0.0001 and 0.1; all of which are plausible values for live wood at a low frequency.

Table 4.2 shows the final values for both conductivity and permittivity which are used. The conductivity and permittivity can change independently, which is the reason there must be a combination of each which is simulated for. The combination of these values describes a range of situations, in which the temperature and moisture level might be increased slightly or the volume of the simulated tree might not match the dielectric measurement volumes from which they were taken.

Table 4.2: Possible combinations for conductivity in $S\,m^{-1}$ and relative permittivity in simulations

Conductivity	0.0001	0.001	0.01	0.1
Permittivity				
45 - j945	A	B	C	D
230 - j10120	E	F	G	H
3200 - j112000	I	J	K	L

4.1.2 Applied Excitation

A direct attachment to an object is usually modelled by a large current source, with a waveform that follows a similar shape to the voltage waveform described in **Chapter 2**. The applied waveform remains consistent across all simulations. There are several options for the excitation waveform, including double exponential and Heidler functions, each with their benefits and drawbacks.

Conventionally the Heidler function is used, despite the disadvantage of not being able to analytically evaluate it in the frequency-domain [34]. It is used here as the studies will be concentrated in the time-domain and a numerical approximation can be done if needed.

The equation is described in *Equation 4.4* and the values used for the variables are listed in *Table 4.3*. These values are chosen as it is standard (IEC 61312-1 [35]) for the first stroke waveform.

$$i = \frac{i_{max}}{\eta} \frac{\left(\frac{t}{T}\right)^n}{1 + \left(\frac{t}{T}\right)^n} exp\left(-\frac{t}{\tau}\right) \tag{4.4}$$

Table 4.3: Values for Heidler Waveform (10/350μs Short Stroke Simulation)

i_{max}	$100kA$	peak current
n	10	decoupling exponent
η	0.930	correction coefficient
T	19 μs	'front time' coefficient
τ	485 μs	'decay time' coefficient
t	time	usually in μs

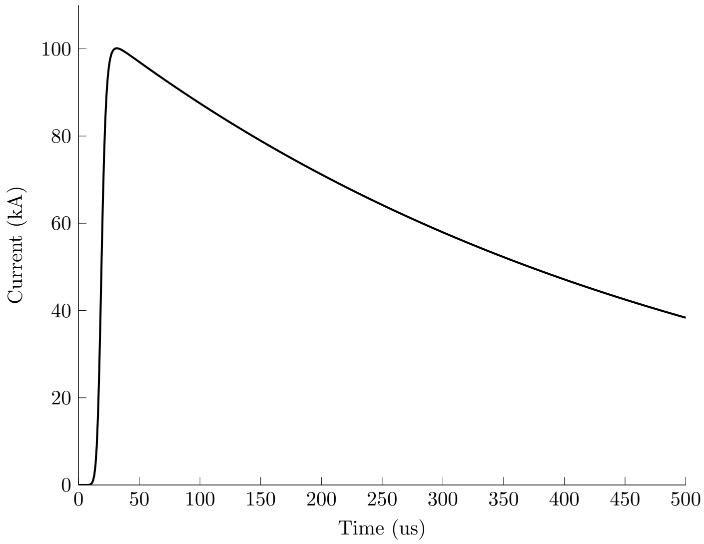


Figure 4.5: Heidler Short Stroke Current Waveform ($10/350\mu s$)

The graph in *Figure 4.5* shows the resulting wave using the values described in *Table 4.3.* As can be seen, the front time is around 10 µs, while the tail time is around 350 µs. This waveform is used throughout the simulations, however the peak current is reduced to 10 kA, as the biological material is volumetrically smaller than the likely natural trees that have a direct attachment and this insures that the breakdown process does not need to be modelled.

Simulation Methodology

The height of the simulations are limited to 2 m long cylinders to simulate the trunk of the tree and allow fringing of the electric fields to occur. The diameter of the wood cylinder is 0.3 m, chosen as it is the width that was measured in the *Elliottii* plantation of eight year old trees.

The instantaneous current is evaluated by using a cross sectional area of the cylinder and integrating the current density vector with respect to the normal vector. This is described in *Equation 4.5* where SA is the surface area (the integral is a double integral for the two dimensional surface).

$$I = \int_{SA} J_x \vec{n_x} + \int_{SA} J_y \vec{n_y} + \int_{SA} J_z \vec{n_z} \tag{4.5}$$

The current density and cross sectional surface in the middle plane is illustrated in *Figure D.3.*

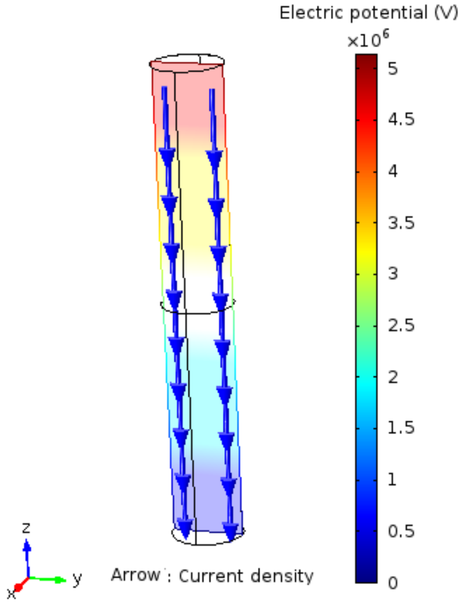


Figure 4.6: Current Density (Arrows) and Electric Potential (ColourBar) for the Wood Cylinder

The results use colour (or grey scale) in most cases to indicate the conductivity and line type to indicate the permittivity as each current will indicate current through a vessel when the wood has a certain permittivity *and* conductivity. This means that both the line type and colour are indicators in the graphs. Occasionally the different line types are used to indicate current or power loss in different vessels, but this is described in more detail when the graph is presented.

As the current density varies throughout the cylinder, the current is not likely to be identical at each point within the cylinder, but evaluating the current at a certain distance from the source will give an indication of the current throughout. The halfway point is selected as it is closer to neither the source nor ground.

The resistive power loss (along with current) is used as a means of evaluating the damage experienced in each of the channels as the power loss, in Watts, is a measure of the heat that the substrate experiences. The resistive power loss is calculated by integrating the resistive power loss density for the volume of the cylinder. This can be seen in *Equation 4.6*. The instantaneous power loss vector is the current density vector multiplied by the electric field vector.

$$\text{Power Loss} = \int_V \vec{Q_{rh}} \tag{4.6}$$

Ground Terminal

The ground is considered an ideal ground to reduce complexity. As this is not the focus of the dissertation, it can be considered at a later stage by modifying the ground layer properties. However, as the surrounding air is considered within this investigation, the ground terminal can either be chosen as only the bottom of the tree cylinder (treating the tree cylinder as a conducting wire) or continue into the bottom of the surrounding air cylinder. The described model can be seen in *Figure 4.7*. The larger ground plane consists of both the air and wood ground surfaces.

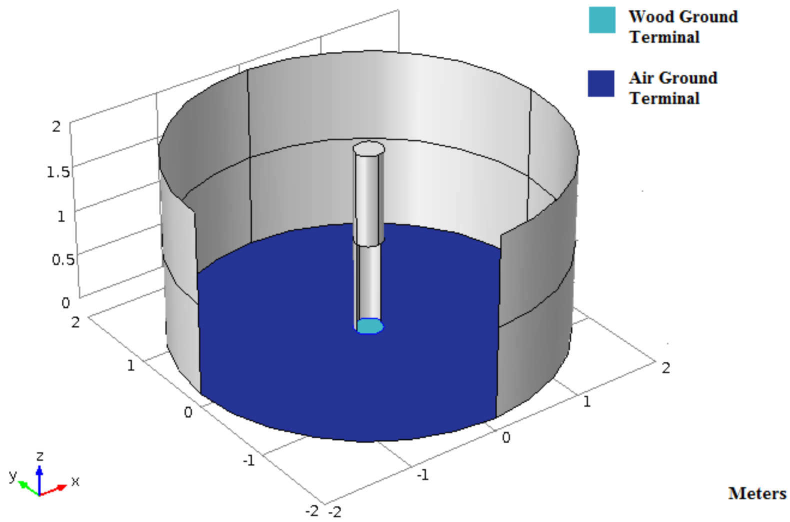


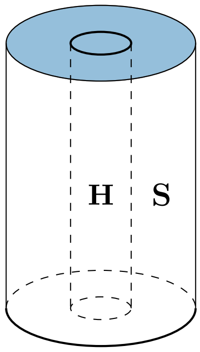
Figure 4.7: Model setup for comparison of ground terminals

By investigation, which can be read in **Appendix D**, even though the difference is not large between the smaller and larger ground planes, the larger ground will be used as this more closely resembles the natural state which is intended to be simulated.

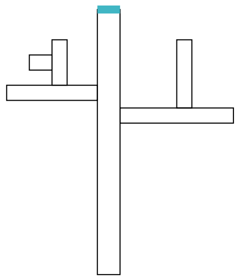
Application Terminal

The application terminal (shaded area) for each of the simulations can be seen in *Figure 4.8* for the macro geometry *Figure 4.9* for the heartwood and macro geometry tests.

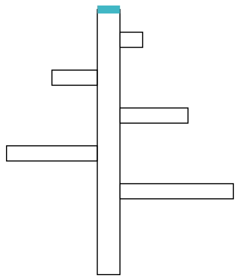
In all cases, except where the water channel is outside the wood cylinder the source is applied to both the wood and water channels as a surface terminal. While a point or edge terminal is also a possibility, these are not considered in this dissertation as it increases the scope and computational requirements beyond what is needed for the inferences.



Heartwood test (**H**: Heartwood, **S**: Sapwood)



Comparison tree (Two dimensional test)



Pine tree (Two dimensional test)

Figure 4.8: Source terminal indication for heartwood and macro geometry tests

4.2 Heartwood Test

As mentioned previously, the pine species in particular has a noted difference between the heartwood and the sapwood. To investigate this, a simple two-cylinder model is constructed with the heartwood in the center. This is illustrated in *Figure 4.10*.

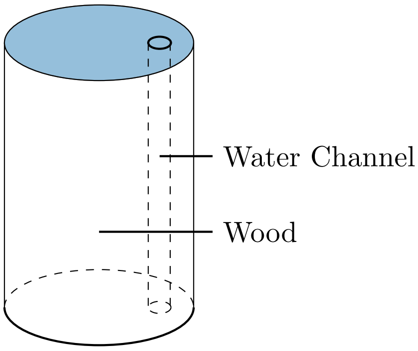
The radius of the heartwood differs in trees of different ages, so multiple sizes were selected. In this particular case, the conductivity and permittivity of the heartwood and sapwood are fixed, as given in *Table 4.4*, to isolate the effects of the heartwood volume rather than the dielectric properties. The values are adapted from *Guyot* in *Table 4.2* [26].

Table 4.4: Conductivity and permittivity used in heartwood test

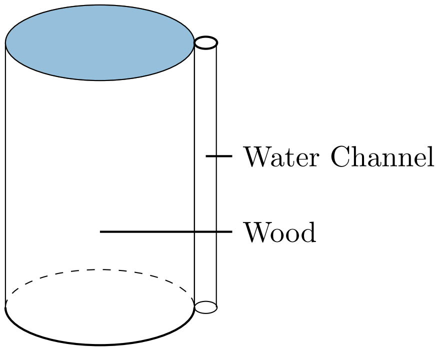
	σ [S/m]	ϵ
Sapwood	0.004	230 - 44*230j
Heartwood	0.0004	94 - 13j

Instantaneous Current

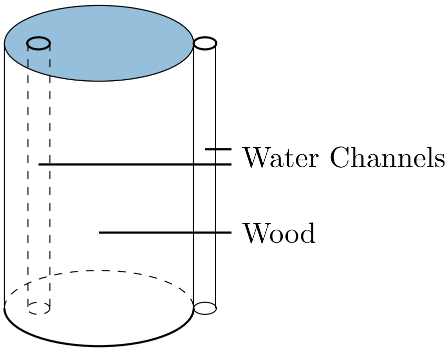
The current is then calculated by integrating the current density of the surface in the midplane of the vessel. The ratio of heartwood to sapwood was increased and the current recorded for each. The graphs in *Figure 4.11* indicate the various percentages of the heartwood volume in the wood and the solid lines show the current magnitudes through the sapwood.



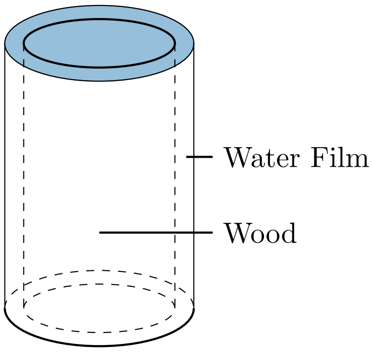
Case A: Internal water channel



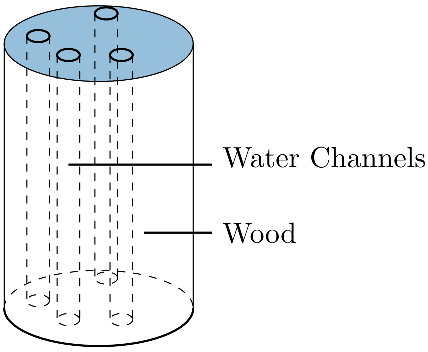
Case B: External water channel



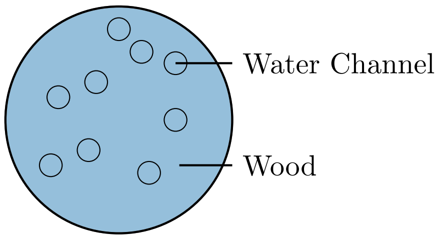
Case C: Internal and external channels



Case D: Water film



Case E: Multiple distributed internal water channels (Not all channels included)



Case E: Top-down view of placement of multiple water channels

Figure 4.9: Source terminal indication for all water tests

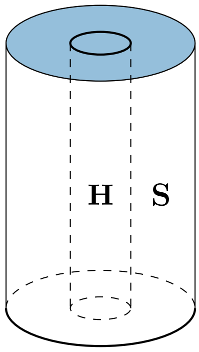
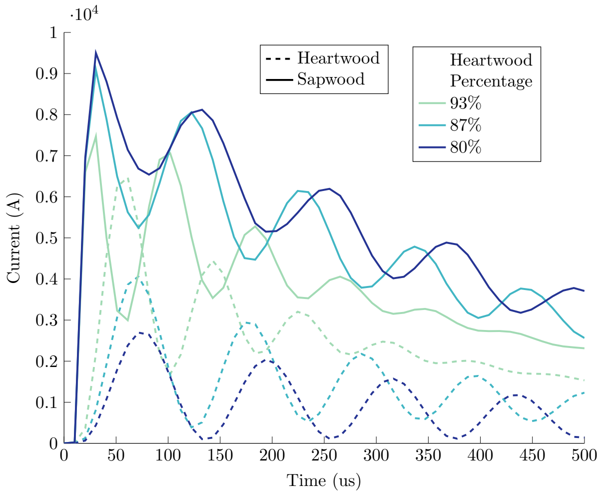
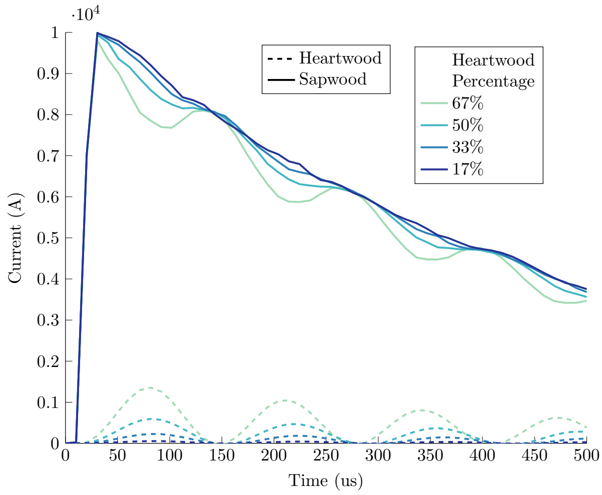


Figure 4.10: Heartwood test geometry (**H**: Heartwood, **S**: Sapwood)



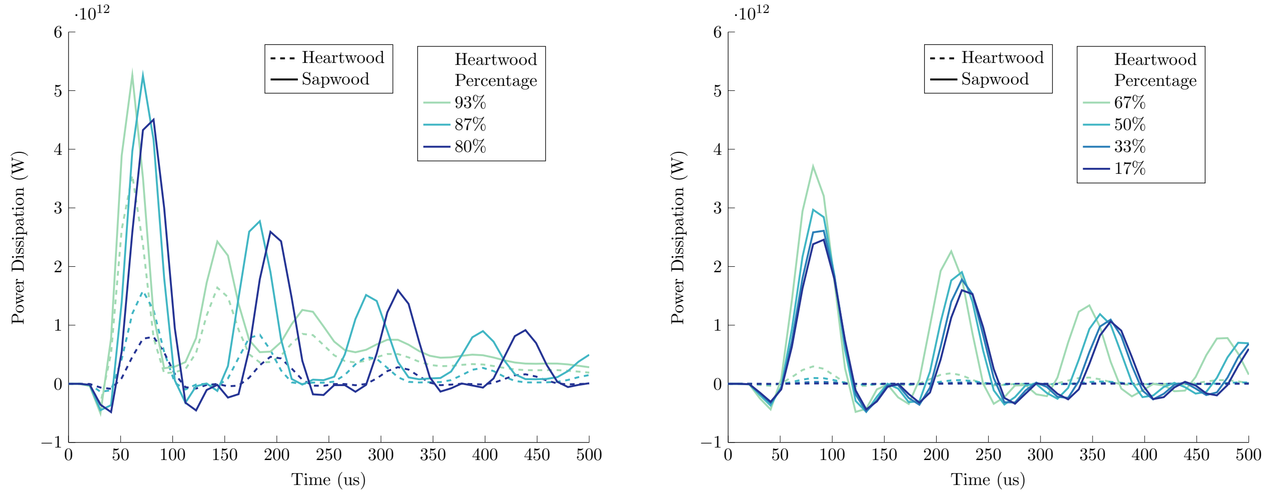
(a) Larger heartwood volumes



(b) Smaller heartwood volumes

Figure 4.11: Current through midplane of heartwood and sapwood for various heartwood volumes

It is evident that the current is exchanged between the heartwood and the sapwood and that as the percentage volume of heartwood increases, the amount of current transferred in the exchange increases. As the sapwood has a larger conductivity than the heartwood, it is reasonable that the current would be greater in this channel. As the size of the sapwood decreases, the electric fields allow for the heartwood to develop a current that increases and decreases sinusoidally with a frequency around 6666Hz for the smaller heartwood percentages and slightly higher for the larger heartwood percentages. These smaller percentages are more realistic volumes for trees [36].



(a) Larger heartwood volumes

(b) Smaller heartwood volumes

Figure 4.12: Instantaneous resistive power dissipation of heartwood and sapwood for various heartwood volumes

Resistive Power Loss

The instantaneous power dissipation that occurs in the heartwood and sapwood volume is shown in *Figure 4.12*. For the smaller heartwood volumes, the power dissipation and therefore heat, is largely within the sapwood; however, as the heartwood percentage increases, so does the power dissipation magnitude in the heartwood. The more heartwood there is (with the lower conductivity), the more power is dissipated in both the heartwood and sapwood.

As the current decreases in the sapwood and increases in the heartwood after the initial rise, the power dissipation increases and reaches a peak as the peak in the current in the heartwood is reached. This interaction can better be observed in *Figure 4.13* which has both the current and power dissipation over the same time to better observe the trends and interactions.

4.3 Water Tests

The following tests were conducted to see what effect a water channel would have at various positions and geometries with respect to the trunk. *Table 4.5* captures the aims of each of the tests, the geometry of which can be seen in *Figure 4.9*. The current is measured as the surface integration of current density on a plane midway through the channel from source to ground. It gives an indication of the current values for a particular point over time that can be compared for all geometries.

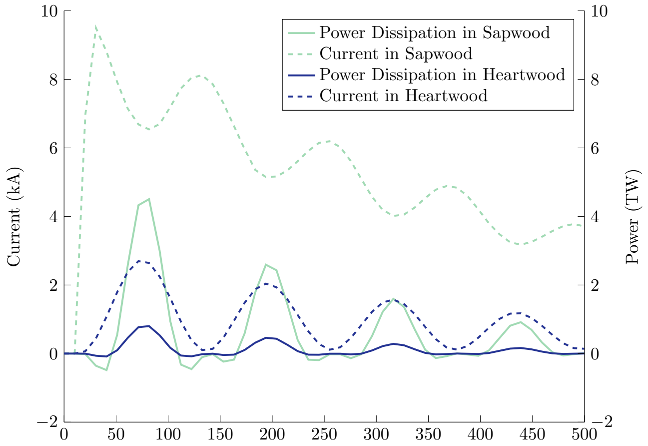


Figure 4.13: Current and power waveforms for 93% heartwood volume

Table 4.5: Summary of water tests with aim of each test

Model	Test
A: Internal Water Channel	Location and Water Channel Effect
B: External Water Channel	Location and Water Channel Effect
C: Internal and External Water Channel	Double Volume with Location Effect
D: Water Film	Smaller Volume with Geometry Effect
E: Multiple Distributed Internal Water Channels	Larger Volume and Geometry Effect

The dielectric properties for the water are from *Rusiniak's* research, chosen at 10 kHz [37]. The conductivity is $0.223\,\mathrm{S\,m^{-1}}$ and the relative permittivity is $1500 + \mathrm{j}1500$. These values are assumed not to change so as to simplify the problem, but in a natural case the dielectric properties change with temperature and ionic content.

4.3.1 Case A: Internal Water Channel

The wood cylinder seen in *Figure 4.14* is the same that is used throughout. The water channel with a radius of 0.015 m is placed 0.075 m from the center.

Case A: Instantaneous Current

As a wide range of situations is represented by the dielectric values and conductivities of the wood, the resultant current is divided into the three specifications of permittivity values to better distinguish them. In each range of conductivity the current through both the water channel and wood is depicted.

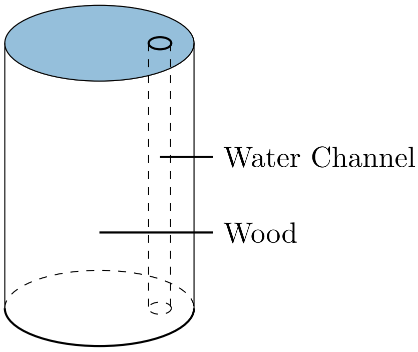
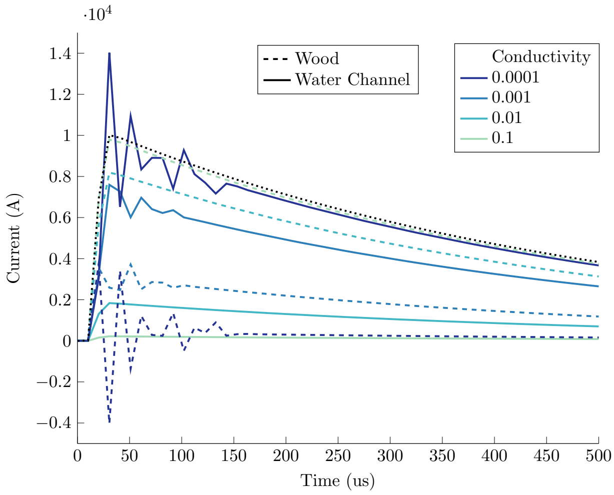
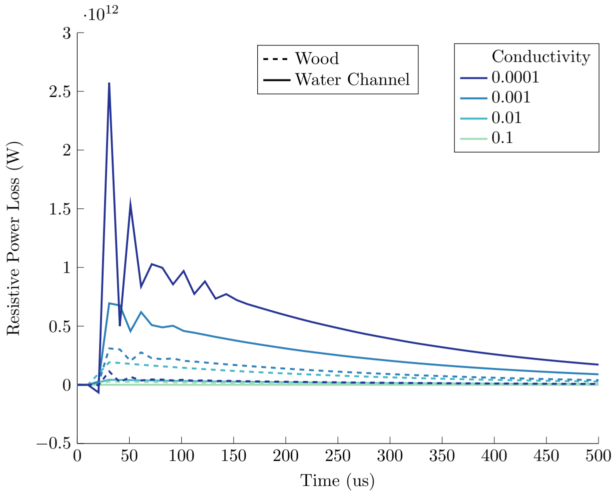


Figure 4.14: Case A: Internal water channel

Figure 4.15 shows the whole range of current and power loss for the smaller permittivity value of $45 + 945j$, *Figure 4.16* shows $230 + 10120j$ and *Figure 4.17* shows the current and power loss for conductivities with the largest permittivity $3200 + 112000j$. From these figures, a distinct difference is observed in the response of the current as the permittivity is increased. Within each permittivity value, the effect of conductivity can also be observed.



(a) Current through water and wood

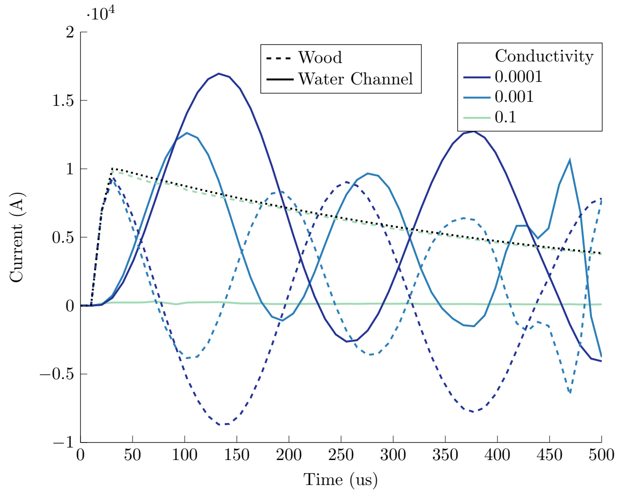


(b) Resistive power loss of water and wood

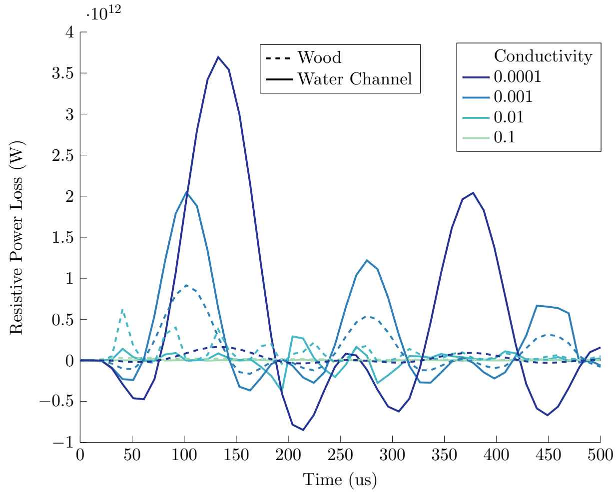
Figure 4.15: Case A: Internal water channel test - Permittivity 45 + 945j

When the wood has a smaller permittivity value as in *Figure 4.15*, the role of the conductivity is more prominent than the permittivity as the current divides between the water and the wood evenly according to the conductivity. For the smaller wood conductivity values of $0.0001\,\mathrm{S\,m^{-1}}$ and $0.001\,\mathrm{S\,m^{-1}}$, the current is largely in the water, whereas the larger conductivity values of $0.01\,\mathrm{S\,m^{-1}}$ and $0.1\,\mathrm{S\,m^{-1}}$ show the current passing mostly through the wood instead.

When the permittivity value is increased as in *Figure 4.16*, the division is still evident, but the electric field storing ability plays a larger role than before as it allows for a sinusoidal exchange of current between the wood and the water.



(a) Current through water and wood



(b) Resistive power loss of water and wood

Figure 4.16: Case A: Internal water channel test - Permittivity 230 + 10120j

One way of understanding the current graphs is that after the initial rise in the applied impulse function, the source current decays and varying branches of currents will be present throughout the wood, setting up their own magnetic and electric fields. The low conductivity of the wood, coupled with the high permittivity values present, allow for a current to set up in the water channel in response to this. While the magnetic effects are not being included in the model, they are still present.

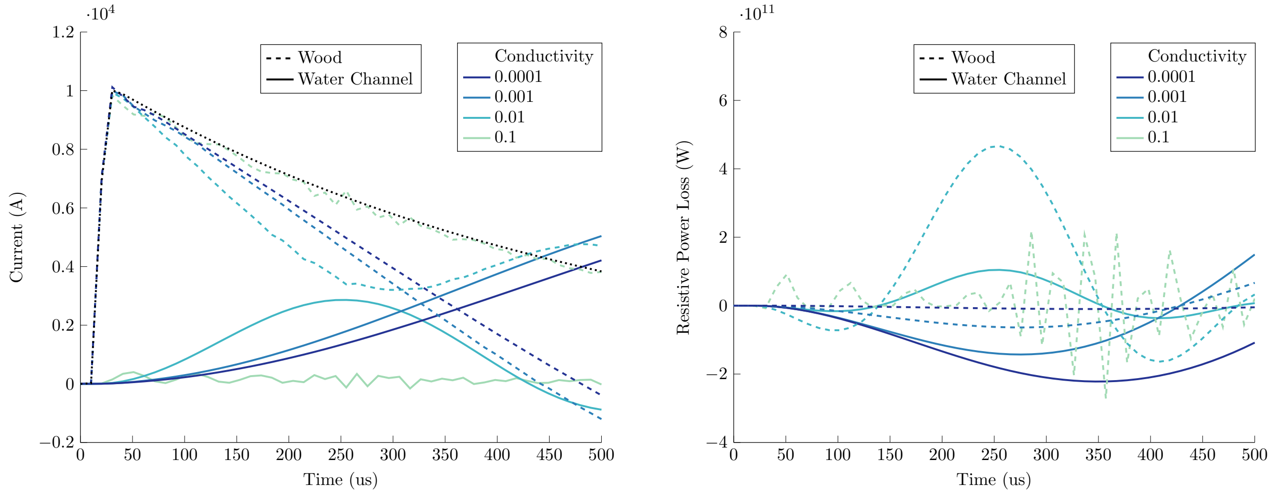
The current now cycles though the water and wood channel individually, while still summing to the applied current as conservation of current must hold true. This means that the instantaneous values for current through either water or wood can be more than the applied source at that point in time as the current through the other channel will oppose it.

This is only possible when the conductivity of the wood is very low as the water channel then presents an attractive path of less resistance. This is apparent in that the current is entirely in the wood for the conductivity value of $0.1\,\mathrm{S\,m^{-1}}$, regardless of permittivity.

As the permittivity is increased further to $3200 + 11200\mathrm{j}$, as in *Figure 4.17*, the exchange in current between the wood and water takes longer as the storage capacity is larger. The exchange still starts to occur as the source starts to decrease and the conductivity effects the time constant of exchange as well.

Case A: Resistive Power Loss

Similar to the current graphs in the previous section on page 32, the resistive power can also be separated by permittivity, affirming the trends seen in the current.



(a) Current through water and wood

(b) Resistive power loss of water and wood

Figure 4.17: Case A: Internal water channel test - Permittivity 3200 + 112000j

For higher conductivity values, there is little loss in the wood or water. As the conductivity of the wood decreases, the water channel experiences higher instantaneous power loss. This is to be expected as the power loss is obtained over the volume of the channel and the water channel is 10% of the wood channel.

4.3.2 Case B: External Water Channel

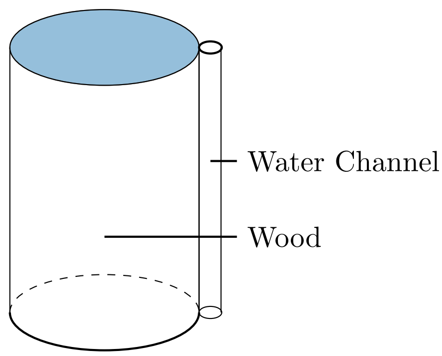
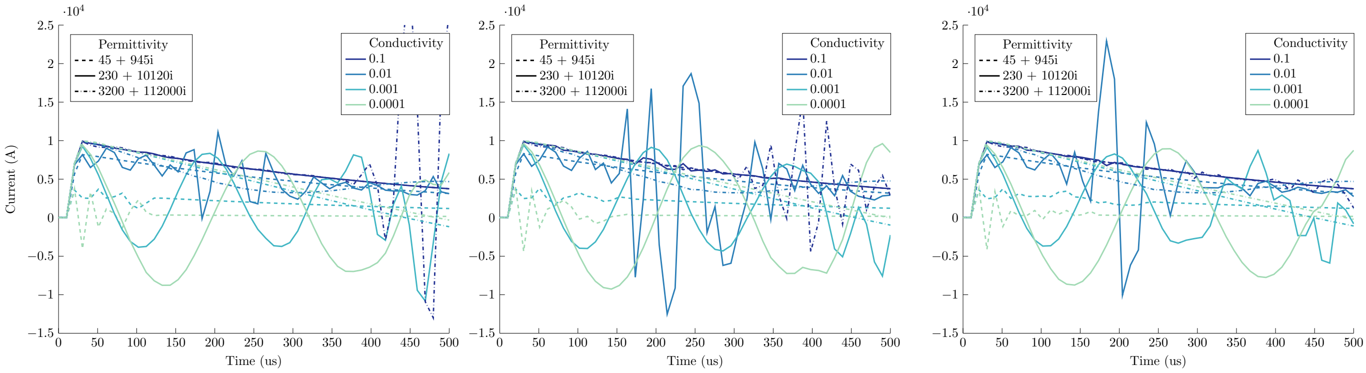


Figure 4.18: Case B: External water channel

Similarly, a water channel along the outside of the trunk was modelled using the same values as for case A, the internal water channel test. This can be seen in *Figure 4.18*. The resultant current graphs which are shown for completeness in **Appendix E**, are almost identical to the ones for the water channel inside the trunk, with some larger values which were determined to have originated from numerical errors in the solver, most likely due to the geometry and the meshing size. A small experiment discussed later whose current graphs represented in *Figure 4.19*, meant to confirm a hypothesis about the placement of the water channel, indicates the likelihood that the errors are from the numerical modelling. A further test to examine if the placement of the integration surface increases modelling errors is also described in **Appendix F**, but it is not found to have a significant effect.

The similarity in case A and B, internal and external channels respectively, is to be expected as the volume of each of the channels has not changed significantly, only the wood volume would increase by the amount of the water channel. The main change that has occurred is that the water channel has moved outward from the source to the perimeter of the trunk. As the fields are responsible for the current flow in the water and the physical boundary is not the major contributor, the currents would behave almost identically in these two situations.



(a) Distance of water channel: 0.02m from center

(b) Distance of water channel: 0.08m from center

(c) Distance of water channel: 0.12m from center

Figure 4.19: Case A: Internal water channel - Discrete distances from the center of wood

A small study was performed to confirm this by moving the water channel along an axis within the wood. *Figure 4.19* shows how the trend in currents for each of these situations are not very different, except for the numerical errors due to course meshing. The numerical errors are amplified as the water channel nears the boundary due to the smaller mesh required to represent the smaller distance accurately. As this was a small study to confirm a particular hypothesis, a coarser mesh than required was deemed acceptable to reduce computational time.

4.3.3 Case C: Internal and External Water Channel

This simulation, seen in *Figure 4.20* modelled both an internal and external channel with the trunk. The internal channel was set on the opposing side to the external channel and the external channel was moved 0.005 m outwards from the trunk to avoid meshing errors.

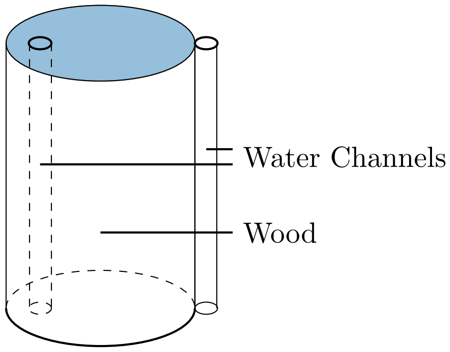


Figure 4.20: Case C: Internal and external water channel

When comparing the current in the wood from the internal water channel test to the current in the wood for this test, only numerical modelling errors could be seen as in *Figure 4.21*. The complete current graphs for Case C (both channels) are shown in **Appendix G**.

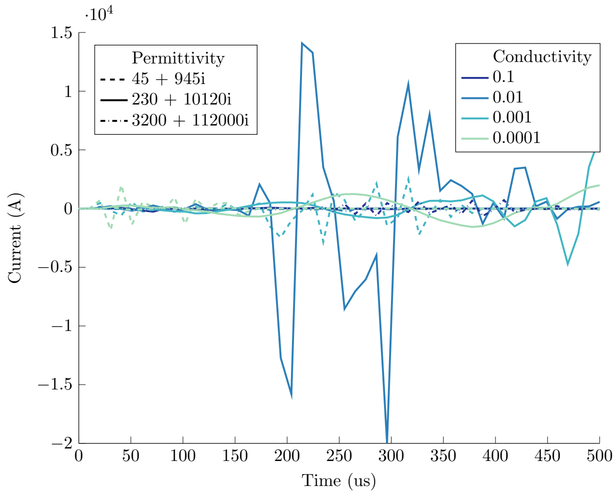


Figure 4.21: Difference between Case A: Internal water channel and Case C: Both water channels

Although the volume of the water has doubled, the volume of the wood is no different to that of case A, the internal water channel. In relationship to the wood, the water amount is only around 20% for two channels, which is still a small amount, but larger than the 10% for the external one.

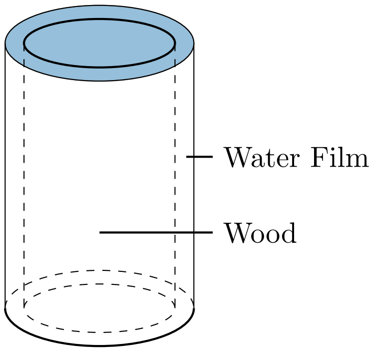


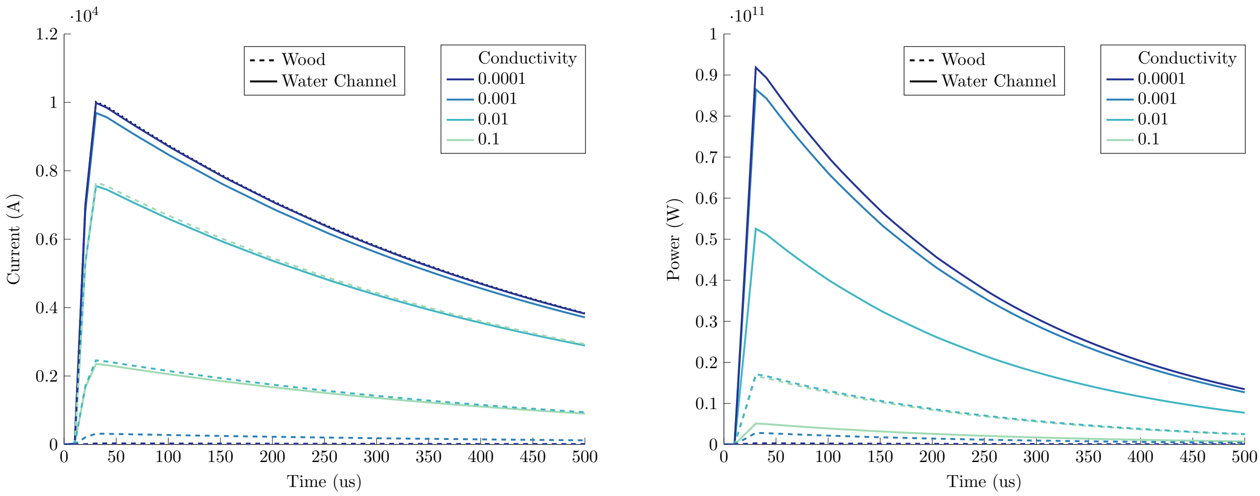
Figure 4.22: Case D: Water film

4.3.4 Case D: Water Film

When the trunk is surrounded by water from rain, a film forms across the outside of the tree bole, this can be seen in the geometry for the test as in *Figure 4.22*. This is geometrically very different from a channel along the outside as there is water on every side of the trunk, not just one. The volume of water is also increased in the film test, from $0.001\,41\,\mathrm{m}^3$ for a water channel to $0.0194\,\mathrm{m}^3$ for the water film.

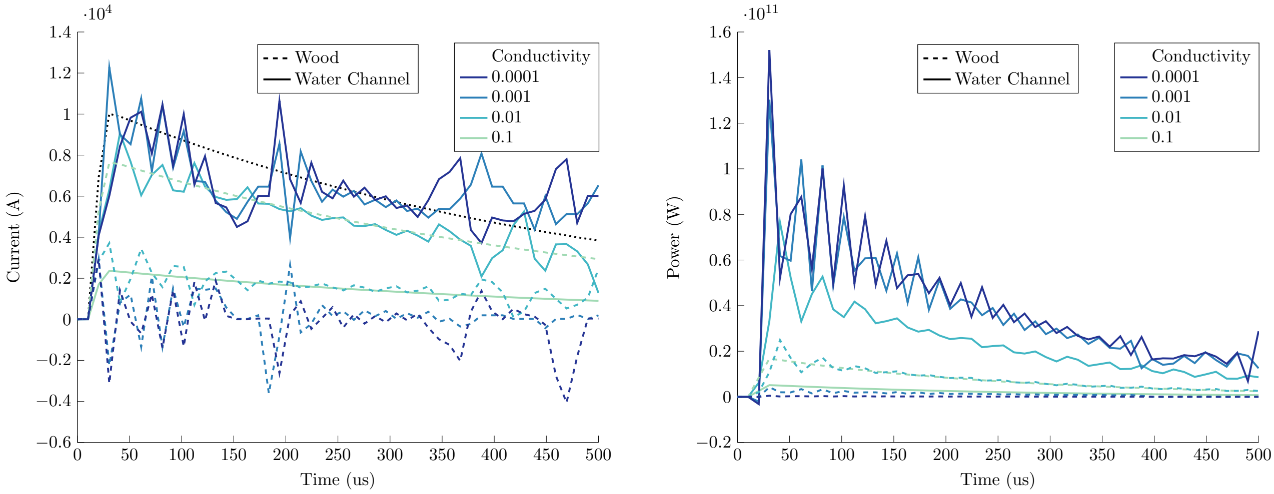
The three possible permittivity values show clear trends and are thus individually represented in *Figure 4.23*, *Figure 4.24* and *Figure 4.25* for 45 + 945j, 230 + 10120j and 3200 + 112000j respectively.

As before, the conductivity and permittivity of the water is set and does not change, unlike the wood. The size of the water film is not chosen to imitate what would occur in a natural storm, but to test whether the geometry and volume of the water will influence the current. It is therefore exaggerated to easily infer behaviour.



(a) Current through water and wood
(b) Resistive power loss of water and wood

Figure 4.23: Case D: Water film test - Permittivity 45 + 945j



(a) Current through water and wood

(b) Resistive power loss of water and wood

Figure 4.24: Case D: Water film test - Permittivity 230 + 10120j

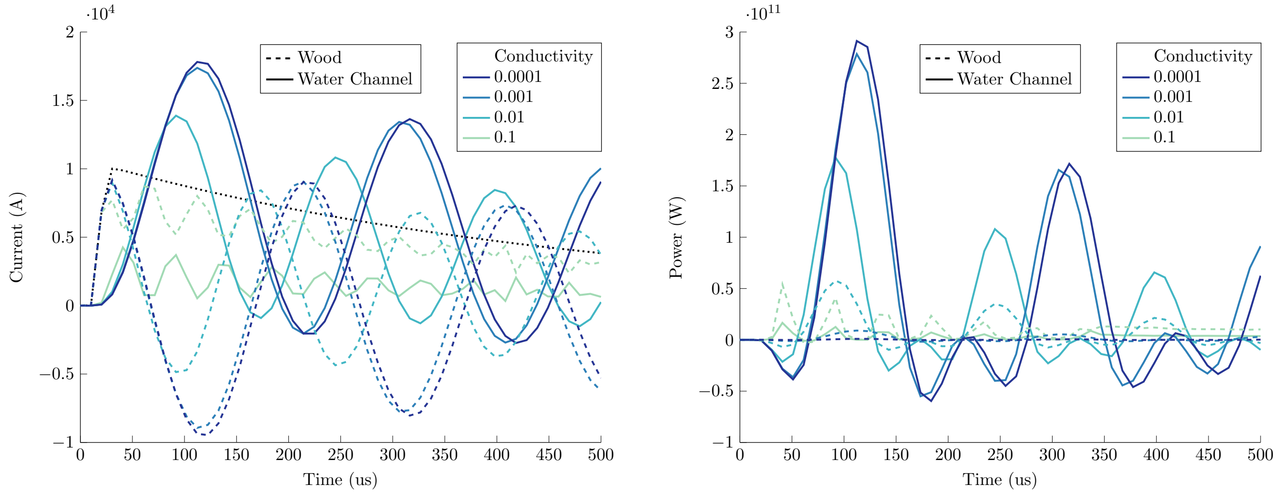
Case D: Instantaneous Current

The smaller permittivity value illustrates how the conductivity controls the current magnitude in the water and wood as there is a clear division occurring. When the conductivity of the wood is low, the majority of the current is in the water channel. It is interesting to note that the higher conductivity values of $0.1\,\mathrm{S\,m^{-1}}$ and $0.01\,\mathrm{S\,m^{-1}}$ are the exact opposite of each other, in that the same amount of current is present in the water for one, as there is in the wood for the other at the same point in time. This is likely due to the conductivity and volume being balanced.

Unlike the previous tests, the current is not wholly in the wood for conductivity value $0.1\,\mathrm{S\,m^{-1}}$, which indicates that the increase in the volume of the water has affected which material has less impedance to the current.

When the permittivity is 230 + 10120j the electric fields have more of an affect, in that there is a cycling of current that is occurring between the water and the wood. The sharp spikes are also due to numerical inaccuracies from the software. The numerical inaccuracies are left as captured in the data for interests sake, but the erratic behaviour being highly likely from mathematical noise has been discussed in **Section 4.3.2**.

Only the highest conductivity value of $0.1\,\mathrm{S\,m^{-1}}$ has no ringing. The division of current between wood and water remains the same as for the previous permittivity (45 + 945j).



(a) Current through water and wood

(b) Resistive power loss of water and wood

Figure 4.25: Case D: Water film test - Permittivity 3200 + 112000j

The largest permittivity shows an increase in the magnitude of the peaks of the exchange as well as an increase in the period of exchange for all conductivity values. The current for the wood and water still sum to the applied value, but the individual current experienced is much larger. The lower conductivities, $0.0001\,\mathrm{S\,m^{-1}}$ and $0.001\,\mathrm{S\,m^{-1}}$ have almost the same current for water (and wood) for this highest permittivity value of 3200 + 112000j. The current for the largest conductivity has also started to exchange between water and wood, whereas it did not when the wood had a smaller permittivity.

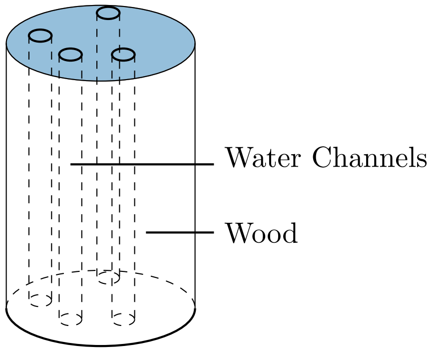
Case D: Resistive Power Loss

The resistive power loss for the water film tests (case D), behaves as expected for these current trends. It is very similar to the power loss in relation to the current for the heartwood volume test described in **Section 4.2**.

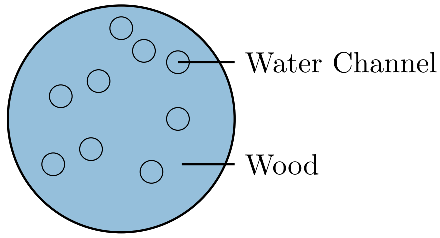
4.3.5 Case E: Multiple Distributed Internal Water Channels

Having a distributed system of water channels more closely resembles a natural trunk, but the values chosen for the radius of the water channels is exaggerated to test for geometrical and volume effects rather than parallel a tree.

The radius of the wood is the same as all previous tests, as is the radius of the water channels, but there are nine water channels in total, distributed around the trunk in no particular order. A cluster of three exists in one quadrant to allow for any interactions to occur where proximity is necessary. This can be seen in *Figure F.1*.



Case E: Multiple distributed internal water channels (Not all channels included)



Case E: Top-down view of placement of multiple water channels

Figure 4.26: Case E: Multiple distributed water channels

The current trends followed those of the water film test closely. A comparison of the current through the wood can be seen in *Figure 4.27* and *Figure 4.28* for the smallest and largest permittivity values respectively.

Just as in the previous tests, the smallest permittivity value for the wood shows no ringing the current. As the conductivity decreases, the magnitude of the current in the wood is reduced as well. There is a small difference between the current in the wood for the water film test and that of the multiple channel test.

When the permittivity is increased, the difference between the tests is more obvious. While there is a similar exchange in current as before, the frequency of the exchange has changed from around 5000 Hz in the water film test to around 3333 Hz in the multiple channel test for the same conductivity value of $0.0001\,\mathrm{S\,m^{-1}}$. The lowest conductivity has the highest frequency change, which is only slightly evident in the highest conductivity value.

4.4 Macro Geometry

As a complimentary investigation, a two dimensional comparison of the effect of the macro geometry of two trees is studied. A pine tree, modelled after the *Pinus Elliottii* and a general "bushy" tree such as the *Sclerocarya Birrea* or Marula tree is used.

The specific growth pattern of most trees is a complex process involving many factors such as wind, weight and water availability, amongst others. While there are some investigations into modelling the tree growth mathematically, these are beyond the scope of what is necessary [38].

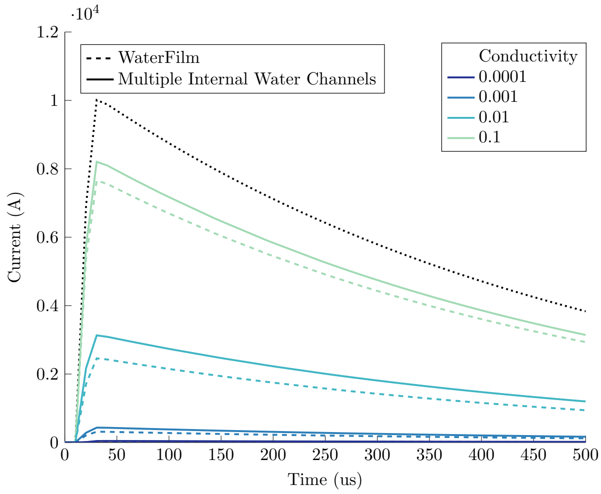


Figure 4.27: Current through wood for Case E: Multiple water channel test and Case D: Water film test - Permittivity 45 + 945j

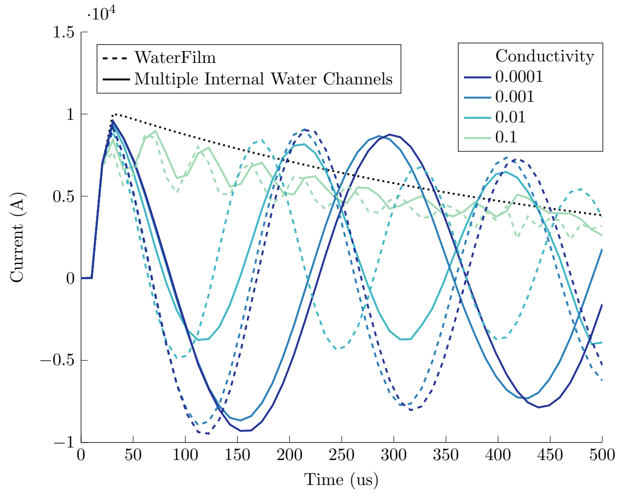


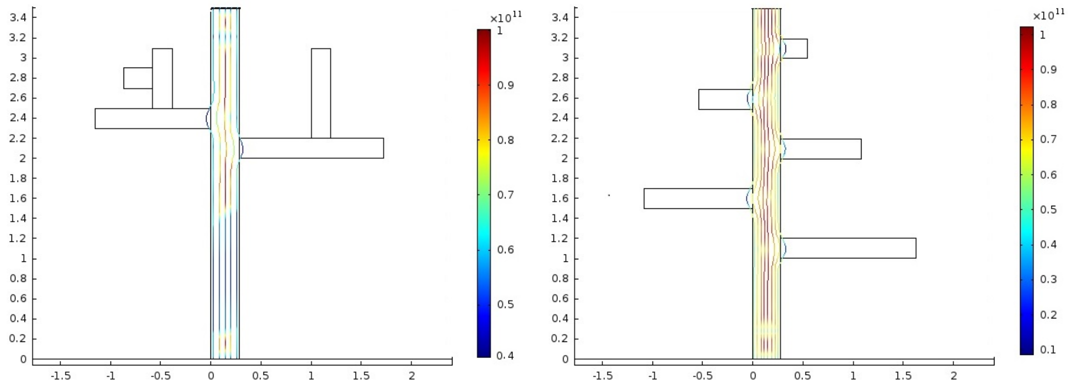
Figure 4.28: Current through wood for Case E: Multiple water channel test and Case D: Water film test - Permittivity 3200 + 112000j

Therefore the following limitations were placed on the simulation:

- The pine tree has a spiral growth pattern
- The comparison tree has a bushy growth pattern
- The investigation is modelled in only two dimensions
- The surface area of both trees is identical
- A central trunk is the same height and width for both
- The Heidler current waveform is applied at the same point on the top edge of the trunk

Figure 4.29 shows the resultant set up and current density streamlines for both the pine and comparison tree. There are large differences in a two-dimensional simulation compared to a three-dimensional one since the effect of the volume and three-dimensional shape is not included. In these specific tree related simulations the branching currents do not have three dimensions to develop in and the electric fields storage effect is minimalised. The consequences of this is that the permittivity and conductivity had no effect.

The current density for each of the permittivity and conductivity values is not altered in any way, nor is the progression of the instantaneous resistive loss. *Figure 4.29* shows both the comparison and pine tree at the same point in time (60 µs) for the same permittivity and conductivity value ($0.01\,\mathrm{S\,m^{-1}}$ and 230 + j10120).



(a) Comparison tree configuration (b) Pine tree configuration

Figure 4.29: Macro geometry tree tests with current density streamlines

It is evident that there is a flow of current towards the branches in both the bushy and pine tree, but the summed surface area for one attachment point from branches to trunk has no visible effect on the amount of current through the branch. When a branch is present, the current density is altered from the direct route towards ground by moving into the branch.

There is a difference between the bushy growth habit and the spiral growth habit that is unmistakable in the resistive power loss. The power loss is less where there are no branches present as the trunk of the comparison tree has less power dissipation occurring. By adding more branches and therefore more boundaries, the power loss is larger along the entire pine tree than the comparison tree.

The lower branch on the comparison tree was moved to below the midpoint of the trunk, which can be seen in *Figure 4.30* to verify this argument. By spreading the branches, the resistive power dissipation, which is heat, is once again higher along the entire tree, even though this is still the bushy growth habit.

Conclusion

This chapter documents the various simulations performed and summarises the results obtained from each in the form of current and resistive power loss. The heartwood, water and macro geometry tests were each performed with similar basic models but tested different aspects of the interaction of lightning with a pine tree. The next chapter will give reasons as to what the most likely explanation for these results are.

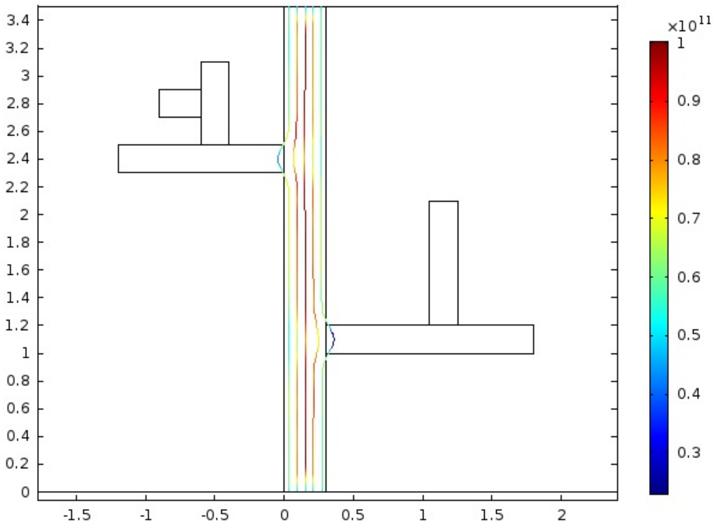


Figure 4.30: Macro geometry comparison tree with lowered branch

Chapter 5

Analysis and Interpretation

Overview

This chapter discusses and analyses the results obtained in the previous two chapters. The experimental and modelling work is discussed separately and then a broader overview is given that encompasses all the work of this dissertation. Some inferences can be drawn about the interaction of lightning and pine trees.

Lightning is a stochastic field of research, the interpretation and inferences in this dissertation are based on the results presented, which aim to conceptualise lightning as correctly as possible. The current and voltage waveforms that are used are statistically the most likely to occur, but it is not definite which specific impulse or magnitude will be present when a lightning stroke occurs.

5.1 Experimental Work

There is difficulty in performing experiments in a laboratory that can give good indications of natural lightning phenomena in terms of the interaction with living material. This is due mainly to the high energy requirement and the unpredictable nature of lightning itself.

The experimental work with resin indicates mainly the high impedances that the tree material has. This is also apparent when the conductivity values for low moisture content wood is considered. Even the values for the living wood that were chosen for the modelling work in **Chapter 4** would not point to a *conductive* material.

However, it is clearly evident from the tree tissue tests that a minimum level of moisture content is required for breakdown to occur, which was not present in the tests. The tracking shows an interesting effect of dry wood in combination with impulse applications of voltage which is beyond the scope of this dissertation as living tissue is the primary focus.

The ringing seen in the leakage current for the resin test which was initially thought to be an artefact of the impulse generator could be a result of a high permittivity value, as seen in the modelling work. This would imply that the resin allows for the exchange of current to occur within the various constituents. However, as the permittivity of the resin is unknown, this is an hypothesis based on the similarity of the waveshape.

5.2 Modelling Work

Based on the simulations performed in *Comsol*[18], several trends were easily identifiable. These trends and observations have been grouped according to the type of test, namely on the volume of heartwood, water and macro geometry.

Each of these tests represents a small subset of natural situations with exaggerated geometries and volumes to determine if what was tested is a major factor in the interaction of lightning and pine trees.

5.2.1 Heartwood

From the heartwood volume tests in **Section 4.2** on page 27 it is discernible that the more heartwood there is, the higher the magnitude of current which is exchanged between the heartwood and sapwood.

Although less current is present in the sapwood for the time of the exchange, the power loss is greater in the sapwood for both the sapwood and heartwood over that same period. This implies that there would be more heat dissipated in the sapwood when more heartwood is present.

This differentiation between sapwood and heartwood is greater in pine trees than other families of trees, which means they are more susceptible to the exchange due to the variation in dielectric values. If a pine tree has a larger amount of dense inner heartwood, the likelihood that it will experience higher damage (due to heating) from a lightning attachment is higher.

5.2.2 Water Tests

The aim of the water tests as described in **Section 4.3** in *Table 4.5* on page 31 tested mainly what effect the water (in channel or film form) would have on the current through the wood and water channels under impulse conditions. The results are categorised in *Table 5.1* by the effect that their volume, location and geometry had on the current magnitude and behaviour.

Table 5.1: Results of water tests

Model	Effect		
	Volume	Location	Geometry
A: Internal Water Channel	–	Not Significant	Exchange
B: External Water Channel	–	Not Significant	Exchange
C: Internal and External Water Channel	Not Significant	Not Significant	Not Significant
D: Water Film	Significant	–	Significant
E: Multiple Distributed Internal Water Channels	Significant	–	Significant

Case A: Internal Water Channel and Case B: External Water Channel

The initial test of having only an internal water channel simulates the internal water vessels that transport mineral water within the tree, whereas the external channel simulates the rain water that could form during a storm.

The internal and external locations had no significant differences in their current magnitudes or behaviours and the resistive power loss showed no difference between the two either. However, the geometry itself[1] has the effect of causing an exchange in the current to occur between the water channel and the wood when the wood has a higher permittivity. This effect was not noted in a two dimensional representation[2].

The conductivity of the wood affects the magnitude of the current within the wood, this leads to a direct effect on the resistive power loss which is the measure by which the damage is assessed as the loss correlates to heat in the material. When the wood has the highest conductivity ($0.1\,\mathrm{S\,m^{-1}}$) there is very little power loss

[1] Cylinder and cylinder
[2] Rectangle and rectangle

in either the wood or water, whereas when the wood is at the lowest conductivity ($0.0001\,\mathrm{S\,m^{-1}}$), the power loss is entirely in the water channel as this is where the current is greatest.

These two situations are favourable for a pine tree as it would negate heat damage occurring on the tree itself and rather disrupt the water channel. If the water channel is internal however, there might a chance that the vessel no longer functions correctly in the transport of water, which could lead to the slow decay without visible damage.

Between the two extreme conductivity values, the total power loss is reduced as the conductivity is reduced, but is present on both the wood and water channel. In the case of the internal water channel this is undesirable as this would damage all of the tree tissue, making it unlikely that the tree could survive. In the case of the external channel, there is still some power loss that occurs in the wood substrate which is damaging to the tree.

Case C: Internal and External Channel

The effect of the individual channels indicated that a three dimensional geometry using cylinders would allow for an exchange in current over time and the location of the water channel was not of significance. This is unchanged by using both channels simultaneously.

When using both channels, the volume of water is doubled, but the volume of the wood remains the same as the external channel does not subtract from the wood material. As the water is 10% of the wood, this decrease would be significant. However, there is no difference in the current and power loss trends and magnitudes between this and the individual channels.

This indicates that having the same volume of wood in relation to doubling the water is not a significant change in volumes, despite it more closely resembling a trunk in rain than either the external or internal channel individually.

Case D: Water Film and Case E: Multiple Internal Water Channels

Here the effect of the change in volume as well as the geometry changes are deemed significant. This is because there was a definitive change in the behaviour as compared to the individual channels.

A summary of the volumes for wood, a single water channel and water film can be seen in *Table 5.2.* The increase in the volume has a definite effect on the current as can be seen in the trends in the previous chapter.

Table 5.2: Comparison of Volumes of Water in Water Tests and Wood Volume for Complete Cylinder

Wood Cylinder	Single Water Channel	Nine Water Channels	Water Film
$0.14\,m^3$	$0.0014\,m^3$	$0.0126\,m^3$	$0.019\,m^3$

Using a set permittivity value (45 + 945j and 3200 + 112000j) for the wood and comparing the current through the wood for the water film test and the internal water channel test illustrates what changes when the volume and geometry is changed. This can be seen in *Figure 5.1* and *Figure 5.2* for the smaller and larger permittivity values respectively.

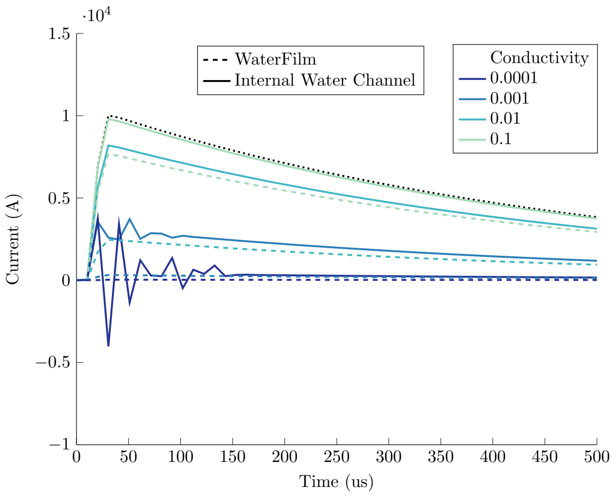


Figure 5.1: Current through wood for Case D: Water film test and Case A: Internal water channel test - Permittivity 45 + 945j

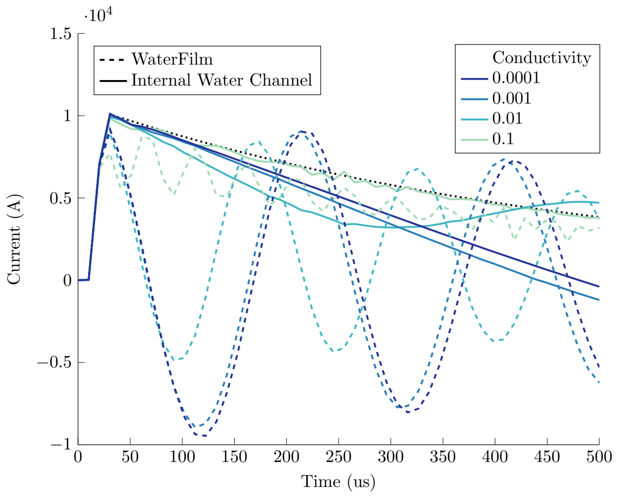


Figure 5.2: Current through wood for Case D: Water film test and Case A: Internal water channel test - Permittivity 3200 + 112000j

For the smaller permittivity, the wood experiences a higher current when there is only a small internal water channel present for the same conductivity value. This is due to there being a larger volume of water in the film, $0.019\,m^3$ compared to the $0.0014\,m^3$ in the single water channel.

Since there is a larger volume of a more conductive material present, the current will more easily pass through it and therefore the current magnitude is higher in the water and therefore lower in the wood. This is also why there is little difference between the multiple channels test and the water film as they have similar volumes of water.

However, when the wood has a larger permittivity value, the behaviour of the current changes significantly. The exchange between the water and wood is still occurring, but the rate is much faster for the water film than the single internal water channel. One possibility is that the volume of water is larger so there is a larger amount of material with which the electric fields can interact, the other possibility is the distributed nature of the film is influencing the behaviour or a combination of distribution and volume.

As the power loss is present mostly in the water when the current is at a peak in the exchange, it is desirable for the peaks to occur more often before the applied excitation is over as this will limit the damage to the wood. This means a higher rate of exchange would show less damage to a tree.

Following this, the more water is present, the less damage is likely to occur on the wood itself. It is plausible that the more distributed the water, the higher the rate of exchange (from either distributed nature or volume) and therefore less damage is likely to occur on the wood.

To summarise, to show an effect, the volume of water must increase significantly which will decrease the amount of current through the wood and potentially increase the rate at which the current is exchanged between the water and wood.

5.2.3 Macro Geometry

The very simplified macro geometry tests indicate why in some cases of lightning attachment the trees are sheered of the outer layers of tissue as the current is largely along the trunk and shows the greatest power loss at the junction points between the trunk and branches.

While a large amount of instantaneous power is dissipated in both trees, the lower trunk of the bushy comparison tree sustains far less in comparison. This implies that a bushy tree will sustain less damage and trees that have fewer branches attached to the individual branch where the attachment forms are even better protected. The comparison tree is more likely to survive the attachment from lightning due to the cambium in the trunk not being as heated as that of the pine in a similar situation.

However, this two dimensional simulation is further from the natural interaction than the three dimensional models discussed in this dissertation. The inferences are only indicators of what might be different between two families of trees.

5.3 Broad Spectrum Interpretation

There are several main points which are present in the simulations: Firstly, when the conductivity of the wood is at the largest value simulated ($0.1\,\mathrm{S\,m^{-1}}$), the permittivity is largely inconsequential except in the special case as the volume of the water is increased. In the case of this largest conductivity, the volume of the water and wood determine what the current magnitude is and there is no exchange of current between the wood and water.

Secondly, volume is more important than location or geometry in determining the behaviour of the current. There is a complex interplay between the conductivity, permittivity and volume that determines what the magnitude and frequency of the exchange will be, which starts happening when the conductivity is low and the permittivity is high.

This implies that a species of tree that retains more moisture will be more likely to survive a lightning attachment. The amount of rainfall before and during a storm is also important as more water within or on the tree will also mitigate the amount of damage the wood sustains.

This trend of lack of moisture causing damage also aligns with the theory that old or damaged trees sustain more damage or are more likely to explode since the tissue and vessels are less able to transport water and the tree would therefore likely have less water and a lower conductivity, causing a higher resistive power loss.

Theoretically this also means that if there is a drought followed by a storm with lightning that the trees that are struck during a drought will probably have more damage than those during the wet season [39].

Conclusion

This chapter has made some observations about the interaction of lightning and pine trees, drawing from a more general view of wood and an applied impulse current. The main factors that determine the damage is the volume of water and the value of the permittivity and conductivity of the wood itself. In the following chapter, the dissertation will be concluded with some reviews of the work and future recommendations.

Chapter 6

Conclusion and Recommendations

To answer the question posed initially as the focus of this dissertation: **The factor of the tree which is important in determining the amount of damage sustained from a lightning attachment is the amount of moisture.**

This is the simplified answer as there is a more complex interaction between the water and the tree tissue itself, changing the conductivity and permittivity values of the tree material. These values determine the behaviour of the current when a direct attachment to the tree occurs, along with the volume of water due to external forces such as weather conditions.

In general, when the tree has a higher conductivity (likely from a higher moisture content), there is less heating (from resistive power loss), which means less damage to the tree tissue. The geometry and location of the water was found to not be as significant as the volume, which means that the species of tree (through density, water uptake and water transport mechanisms) will play a large role as they retain different amounts of water.

6.1 Review and Future Recommendations

The inferences are derived from a simulation which encompasses the key characteristics of a tree and water. While these are simplified, they fit in to the intuitive outcome which has been noted in previous works [1].

For a better approximation in terms of the material properties, the temperature dependence of the wood and water could be introduced; however, as the permittivity value is already large due to the low frequency spectrum of lightning, it is not likely to change the behaviour significantly.

A large change in the water volume would significantly alter the magnitudes of the current, so determining the volume of free water within the tree (if it is different to the ratios used here) would make a more accurate representation of a lightning attachment to a slash pine tree. The low moisture content wood would also show indications of an interaction of lightning with an old or diseased tree which would provide insights to the cases of trees exploding.

The dielectric values of the ground were outside of the scope of this dissertation but would affect the path of the current as opposed to the perfect ground assumed in this research. This dissertation focused on the *Pinus Elliottii* as much as possible, but the research could be extended to other trees outside of the *Pinacaea* family.

The work presented in this dissertation gives a preliminary insight into the interaction of lightning and pine trees with a variety of aspects investigated using both experimental and modelling methods.

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Appendix A

SAUPEC Paper on Lightning and Trees

A.1 Preface

The following appendix is a conference paper titled: **An Overview of Research Relating to the Interaction of Lightning and Trees**. It was presented at the *South African Universities Power Engineering Conference (SAUPEC)* held in January 2017, Stellenbosch, South Africa.

A.2 Overview

The paper is a summary of the most relevant literature as it pertains to the interaction of lightning and trees. The initial concepts for the modelling are included in the paper as well.

AN OVERVIEW OF RESEARCH RELATING TO THE INTERACTION OF LIGHTNING AND TREES

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Abstract: A brief summary of the relevant work across multiple fields relating to the interaction of trees and lightning is given. Each aspect drawn from the studies from various fields is interlinked and discussed. The merits of an experimental versus a modelling approach is put forward. Finally, a basic dielectric model is suggested as a next step to gain an insight into the internal response of the tree trunk to a lightning current injection.

Key words: high voltage impulse, tree, wood, lightning, dielectric model

1. INTRODUCTION

The purpose of this paper is to show what research has been done thus far relating to the interaction of lightning and trees, thereby forming a better understanding of what occurs during this process. A modelling experiment is also proposed as the next step in furthering the knowledge of this field of study.

Lightning research has been ongoing for many decades, a greater understanding of which is helpful to prevent loss of life and possessions. It is a particularly difficult subject matter as it is a natural occurrence that cannot easily be replicated or studied in a laboratory. It does not always behave in the expected way, especially when there is an interaction with living matter, such as animals or trees, as there is so much variance in biological tissues.

However, over the years an attempt has been made to quantify the metrics of lightning and fit theories and statistical models to it. As it relates to trees, very little research has been done in comparison to the field of study as a whole. The relevant experimental and modelling research is documented in section 3. and section 4. respectively.

2. TREE COMPONENTS

A brief overview of the generalised tree is given here, with specific mention of resin as it is referred to in the experiments.

All trees will have the same basic layers in their trunk, simplified here in figure 1. Pictured is the bark, phloem, cambium, sapwood and heartwood. The sapwood also has channels formed mostly from dead cells which run from the roots to the leaves, transporting solutes and water upward. The heartwood is a denser collection of the oldest cells and does not have these vessels.

The bark has a protective function and can vary between smooth and rough between different species. The phloem is a thinner layer of living cells that transports sap from the leaves downward to the rest of the tree. The cambium is the layer at which the new phloem and sapwood tissue grows.

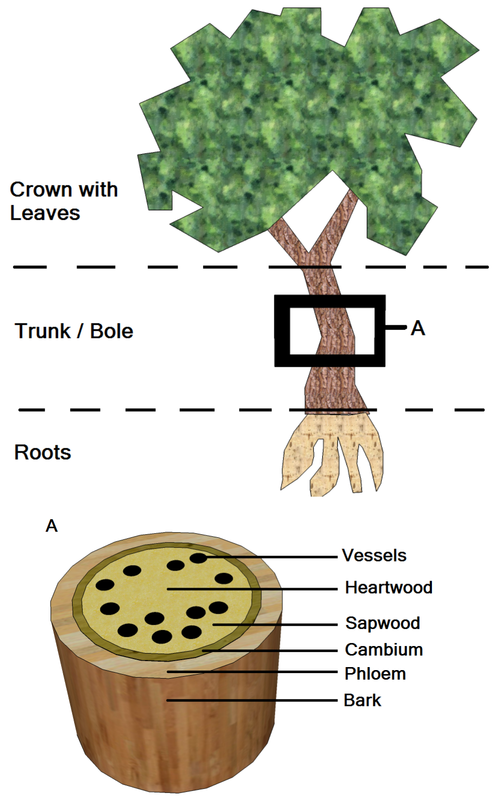

Figure 1: Generalised Cross-section of a Tree

The resin discussed in the following chapter is from the pine tree (*Pinus Elliotii*). The resin is contained within channels that run mainly longitudinally along the trunk, but is present in the branches in the crown as well.

3. EXPERIMENTAL RESEARCH

Since modelling and simulations were not common a few decades ago, there is more experimental data available dating from as far back as 1921. This is a case study documenting a lightning attachment where the current path followed the roots of the tree and was so severe that large trenches were dug following the path of the current [1].

The literature has been divided into experiments performed in the laboratory and in the field, including documented case studies.

3.1 Case Studies and Field Experiments

There is, as of yet, no definitive way of proving a direct attachment to a tree or object and a probabilistic analysis has to be made if there are no eye-witness accounts. There are indicators, such as charring or burning, and the familiar ferning pattern on skin tissue, but these are not always present or are not visible to the naked eye. Most often tearing damage is seen, if there is any visible damage at all, but this can also be due to high winds during storms or age defects. Even in cases where trees that have explosive damage where large pieces of tree matter have been ejected, it is difficult to prove conclusively that lightning was the definite cause.

One theory, which has some case studies to support it, is that positive cloud to ground lightning, which has a higher current magnitudes, causes explosive damage. *Heidler et al* [2] used the appropriate lightning location system to link cases of trees that had explosive damage to the most likely occurrence of lightning. The current magnitude for the two cases of positive cloud to tree investigated, showed over 35kA and over 112kA and resulted in pieces of wood over 30m away from the remains of the tree stub.

Similarly, the data from an appropriate lightning detection network could be used along with the tree's location to determine if positive strikes had occurred in the vicinity of the tree as the previous study had done. This is one way to ascertain whether the damage seen on the tree is from lightning or another source; however, this is not absolutely conclusive and only raises the probability that it is lightning damage.

Some other supporting evidence is found in *Mäkelä et al*'s investigation of 37 cases of lightning attachment to trees [3]. They posit that positive flashes result in more damage than negative and that a high peak value in current magnitude causes more damage. This is inferable, as the higher the peak current magnitude, the higher the amount of energy that is transferred. This knowledge can also be used in conjunction with the detection system to infer the likelihood that it was an attachment to the tree, as with the positive strikes.

This paper also postulates that poor quality trees are more likely to be destroyed by a direct lightning attachment and that it is unclear whether the soil that the tree is growing in contributes to the damaging effect.

The moisture content of the trees is not directly measured and can thus not be used as a factor in the investigation; however, the rainfall was recorded and conclusions can be drawn with regard to water present *on* the tree. In this case, that more water has a negating effect on the damage to the tree. *Mäkelä et al* only link the rainfall to ground moisture and do not make any hypotheses about the moisture on or within the tree.

Another investigation that adds value to the understanding of the interaction is that of *Taylor*. His observations show that if a tree has a furrow on it's trunk due to a previous lightning attachment, then a second attachment will likely cause ignition [4]. In this case, no measurements are made of the peak current amplitudes, which play a definitive role and as there is no collection of the electrical properties of the occurrences, the data may be witness biased.

There is not much data present on what the chemical and physical changes are after an attachment, which would make this secondary ignition process far clearer. But there is a dessication effect, also mentioned by *Taylor* [4] and *Mahaney and Milner* [5].

Mahaney and Milner also show that a carbonisation of cellulose occurs on a microscopic level, even though there is no burning observed on a macroscopic scale. Several minerals from the surrounding soil are also fused into the fissures where the lightning current passes, indicating a high peak amplitude, as the temperatures must reach the fusion points of the minerals. It is not recorded whether it is positive or negative, nor what peak amplitude values this attachment had and cannot be numerically correlated.

Further electrical knowledge that is of importance to the understanding of the interaction of lightning and the tree is that wood and living tree matter has a negative thermal coefficient. This is supported through a study done by *Defandorf*, measuring the resistance of a live tree [6]. Using a megger, he determined that the resistivity of a live tulip tree is in the region of 5-10kΩ/cm, but that with multiple applications of current, the resistivity dropped and did not fully recover to the same values. As the standard impulse waveform used for lightning is 1.2/50μs, there is a broad frequency spectrum which the megger measurements do not account for.

Defandorf suggests that there is a filamentary concentration of current that occurs when a lightning attachment has formed. This suggestion would also support the idea that lightning forms a channel which burns out like a filament and is apparent afterwards as a fissure.

3.2 Laboratory Experiments

The paper has shown how field experiments and observations of actual occurrences of lightning have formed a general idea of the interaction. The difficulty in any lightning related field of study is that enormous amounts of energy are required to replicate natural lightning in a laboratory. The waveshape of the voltage and current waveforms can be simulated, but the current required is not easily achieved. The laboratory tests described in the following section are therefore not always a simulation of the natural occurrence of lightning, but they use an impulse or flashover test through which an indication of natural lightning trends can be made.

Wood poles used in cross arms have generally been dried and treated and are no longer considered to be live wood. However, the research performed on poles can still give insight into the interaction of lightning and living trees.

Sporn and Lusignan [7] performed flashover tests on wood poles from two different species, pine and Douglas fir. From this, even though the pine was treated, a clear difference in flashover strengths is seen, where the Douglas fir has a consistently higher flashover strength. This indicates that the flashover strength varies between species enough to make a generalisation of an interaction with lightning and trees less plausible. The species would have to be evaluated separately. It is also apparent in these tests that an increasing moisture level decreases the insulation strength, meaning each individual tree would respond differently to a direct lightning attachment due to the different degrees of moisture present.

Similarly *Darveniza et al* [8] perform impulse tests on wood, using seasoned and unseasoned wood, confirming that the moisture level in the wood is of high importance in terms of flashover strength.

In their tests, the green unseasoned wood sustained more damage; their theory is this is because the path of current flow is internal to the wood causing damage to the tree tissues themselves. When external arcs did occur, there was only slight chipping in the outer layer.

Using these same specimens, repeated impulses were performed and showed that the same breakdown path was not repeated, maintaining the breakdown strength of the wood better.

A small experiment was performed in the high voltage laboratory at the University of the Witswatersrand to determine the breakdown strength of a portion of pine tree. However, it was found that a standard U50 test could not be performed as tracking phenomena caused an early breakdown. This difficulty will be repeated in most tests as the wood samples change after each impulse is applied.

Another test, intended to isolate the effects that resin has on the interaction of lightning and the tree, was performed in the laboratory. The results of this indicated that the resin has a very large impedance and apparatus with higher energy capability is required to perform full tests [9]. This high impedance in resin would likely also contribute to the high breakdown strength that living pine trees have, possibly overriding the effect the moisture level has.

It is important to note that the lightning current will most likely follow the path of least impedance and that wood and trees have a lower impedance than air, particularly when the wood is not dry.

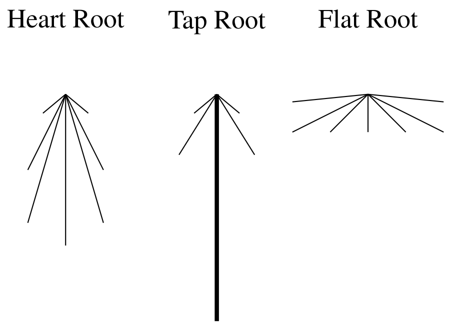

Figure 2: Tree Root Structures

4. DIELECTRIC AND SIMULATED RESEARCH

Simulations of a natural occurrence of a direct lightning attachment to a tree (as closely as possible) in the laboratory are hindered by the difficulties as previously mentioned. This infers that the idea that is formed on the interaction of lightning and a tree is not complete or conclusive enough due to lack of knowledge.

It is clear from the case studies that the moisture level of the tree and path of the current play an import role in the damage that results from a direct attachment. However, in the laboratory it is not easy to see the path that is followed. A simulation would allow for this and give a better indication of what the experimental results mean.

An insight into the macro-geometric effects of trees with respect to lightning and regard to the roots has been briefly evaluated by *Wiater* [10], by modelling the step potential measured a set distance away from the trunk of a tree, varying the root spread type (tap root, heart root and flat root) as can be seen in figure 2. The tap root system shows the lowest measured voltage, while the flat root shows the highest, indicating that the current travels through the root. However, in this case, there are many assumptions that were made that were not fully explained.

For a model, the geometric shape and dielectric properties, along with a software modelling tool and the understanding of the physics needed, are the minimum requirements necessary to construct and perform a simulation test. This can then give insight into the internal mechanisms occurring during an attachment of lightning to the tree. This could perhaps also lead to new hypotheses on the behaviour of an impulse injection to biological matter.

Each tree family varies greatly in macro geometry (the outer shape of the crown and branching pattern), internal and micro geometry (number of cells, cell types and layout thereof), along with the constituents (chemical composition of additional substrates present, such as resin). Between species, though from the same family, there is usually still a large difference in chemical composition and sometimes growth habits; the macro geometry however, is quite similar between them. Each individual tree within the species is also subtly different to the next individual due to unique growth conditions; These include: soil type, moisture availability, weather and surrounding flora and fauna. The model should be constructed with one species in mind, in this case pine is chosen due to accessibility.

Factors needed to model a plant are not readily available and not easily averaged (due to aforementioned unique placement). The best way to obtain the dielectric values needed for the model would be to measure the physical specimen itself.

One method, though only for microwave frequencies, is presented by *Daian et al* [11]. By using a cube of substrate to compare the calculated dielectric property to the measured, assessments could be made about multiple directions of measurements(cross grain, along grain, longitudinal grain). This also proves that the orientation of the impulse injection is significant in the case of natural lightning and when devising the model geometry.

Another difficulty is present, due to the fact that the dielectric values for conductivity and permittivity for wood change as temperature and moisture changes. One attempt to quantify these values was made by *Boutros* and *Hanna* [12] using a sheet of cellulose as a simplification.

The dielectric constant increases with increasing temperature and frequency. An increase in relative humidity and therefore water available in the sample causes an increase in both dielectric loss and the dielectric constant. This is a confirmation of what the experimental research shows, where an increase in the moisture content causes breakdown to occur at lower voltages.

Similar results are found for a set frequency below the range that *Boutros* and *Hanna* [12] used, by *Maeda* and *Fukada* [13]. Here, the frigid temperature effects are mainly investigated, but confirms that the dielectric constant increases with a temperature increase. In their case, using bamboo and cedar, the higher the hydration level, the quicker the dielectric constant would increase. However, the hydration levels were in a narrow range of 0-11%.

While *Chilcott et al* [14] use a different technique and frequency range to model the expected capacitance and dielectric effect, there is a consistency with *Maeda*. Their concept models the tracheids* as a conductance and capacitance in parallel and this unit in series with the pits (microscopic holes between tracheids), which is also modelled as a parallel conductance and capacitance. The pit and tracheids are in parallel with the side wall, which has its own conductance and capacitance in parallel. This evaluates the wood structure on a micro level, but shows similarity to the model which would describe the higher level wood structure.

* Channels through which the solutes and water are transported, similar to the vessels but with slightly different cell types.

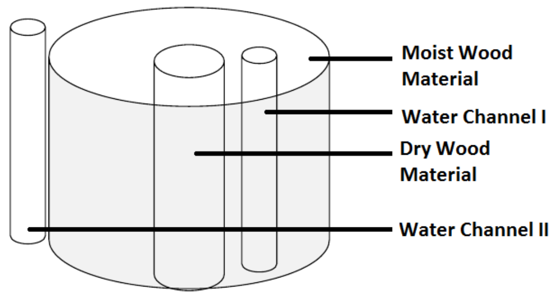

Figure 3: Model of wood bole (trunk) as conductor

This experiment is assessed as the wood sample (pine) is drying, the model therefore needs a unit to describe the diffusion process. This is represented as a conductance and variable capacitance in series added to the previously described circuit.

When comparing this to the measured values, the parameters of the side wall could be ignored due to the orientation of current injection, as the area of the side wall is minimal in this direction. This indicates the relative volume of the different substrates will play a role in determining the overall dielectric value.

This investigates the wood as a dielectric on a far more microscopic level. Once results have been obtained from a macroscopic model, they can be compared to this study to make a more accurate description on the micro level.

5. RELATING RESEARCH HYPOTHESES

A lightning stroke is an impulse and so will have a very large frequency range 1Hz - 300MHz and even detectable above, but the peak frequency spectrum is at 5 - 10kHz [15].

This is the range of frequencies that would need to be simulated. The simplest model to use as a first attempt would be a cylinder with a single dielectric constant which does not alter. However, following the research as previously described, this will not fully explain the phenomena seen in the case studies or the experiments [16]. If further layers are added, such as the bark and cambium, a more realistic model will be formed, but the cost of simulation increases as well.

As seen in the first figure, the center of the tree is the heartwood, which has the highest resistivity. It would be likely that the current would not follow this path, being internal and of high resistance, but it is modelled in this case as dry wood substrate because there is a large variance between dry and wet wood.

While some of the tests in the literature would not accommodate this multi-layered cylindrical model, the orientation of the current injection tests, as done by *Chilcott et al* [14] would. This describes how the path of current flow would most likely follow the grain of the wood, as is clearly seen in lightning scars in all cases mentioned. The reason that the scar is often spiralling or twisting on the tree bole (trunk), is that trees, particularly older ones, rotate as they grow for added structural strength and the grain of the wood would be twisted as well.

Inferring from the previous sections: If the path of current followed is internal, it would likely pass through internal water transport vessels. If sufficient water on the bark formed an external water channel, this would be the most likely path followed by the lightning channel. This is purely dependent on the amount of rainfall and the tree cover density. Both the internal and external water channels as conductors would allow for the filamentary action as described by *Darveniza* [8]. This model is illustrated in figure 3.

If the assumption is made that the path of conduction current is through the internal water and solute channel, a further assumption can be made that the high temperature would vaporise the water, causing cell death around this channel as well. *Anderson et al*'s paper showed how the fissures left by the current do not hold the same moisture as the healthy tissue further from the path, indicating there is indeed cellular damage and that the vessels nearest the fissures are disrupted [17].

This notion is further carried by the likelihood that older and damaged trees sustain explosive damage [3, 4]. If an air pocket (from damaged growth) is present next to the channel or in line with the channel, the heating would vaporise the air, causing some wood matter to be ejected.

Similarly, *Taylor*'s observation that the second occurrence of lightning could cause ignition, seems more understandable as the first attachment would irreparably damage the tree and vessels, allowing the second attachment to cause an ignition, as there is less water flow to protect the tree cells as the current is forced to pass through these instead of water [4]. The ignition could also be because the combustible tree resin with a high impedance is now present on the outside of the tree bole along the fissure line and is heated to burning point by the second attachment.

In general, the moisture level present in the vessel or along the outer bark serves a protective function, by allowing the path of current flow to vaporise the water instead of tree tissues, causing a small fissure and damage localised to the fissure. By inference, tree families that have more water channels or store more water in their trunk, or have rougher bark, would more likely survive (continue to grow for the rest of it's lifespan) a lightning attachment than a tree from a different family.

The trees that have resin would also have smaller channels encapsulated by the highly resistive resin, if these are viewed as separate conduction paths, the electromagnetic force from the impulse would force these apart, causing fissures as well, or possibly igniting the resin.

If, as has been shown by *Mahaney at al* [5], the temperature and energy is enough to cause fusion of minerals and scorched carbon layers, there should be a microscopic method of proving where the main conduction path was during a lightning attachment. However, as these cases are usually associated with an incredibly high peak current amplitude [3], it is unlikely that a lesser damaged tree would show the same micro-fissuring to be able to probabilistically prove where the main conducting current path was.

Though this paper has focused mainly on the tree trunk and not the roots or crown of the tree, there have been some studies on the effect of the roots, as mentioned in the previous section in the study done by *Wiater*. Here, the roots can be seen as a continuation of the conductor model of the tree, which splits or extends differently, based on the root system. This can also be seen by the case study where the root transmitted the current along the ground, forming a furrow [1].

As the roots are more delicate and provide the barrier to the earth through which the nutrients are obtained, it stands to reason that less electrical interference is required to disturb the growth. This would also explain why some trees, though showing no external damage, soon wither and die after an attachment [16]. The step potential would also be detrimental to root health, but is not the focus of this paper.

To include the roots in the initial exploratory simulation model would not be feasible though, as it only adds complications and could cause cross-dependencies. However, these studies do confirm that using a cylindrical multi layer model for the tree is valid.

6. CONCLUSION

A brief overview of the most relevant studies has been given, with a suggested model for simulation. Through this model, the most promising theory: 'Water forms the channel through which the lightning current will flow' can be further investigated. It is unclear whether the water channel that is followed is external or internal to the tree, but the result of the simulation should give insight to this. A simulation model was chosen as the laboratory or field experiments would not resemble the natural occurrence closely enough.

7. ACKNOWLEDGEMENT

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Appendix B

8/20 μs Impulse Generator

B.1 Preface

This appendix presents a diagram of the impulse generator used for the resin impulse experiments.

B.2 Overview

The impulse generator is used in combination mode and has a maximum voltage capability of 20 kV and 10 kA maximum current flow at breakdown when in combination mode. The resin test capsule is placed in the device test terminals described as DUT in the general circuit diagram for the impulse generator.

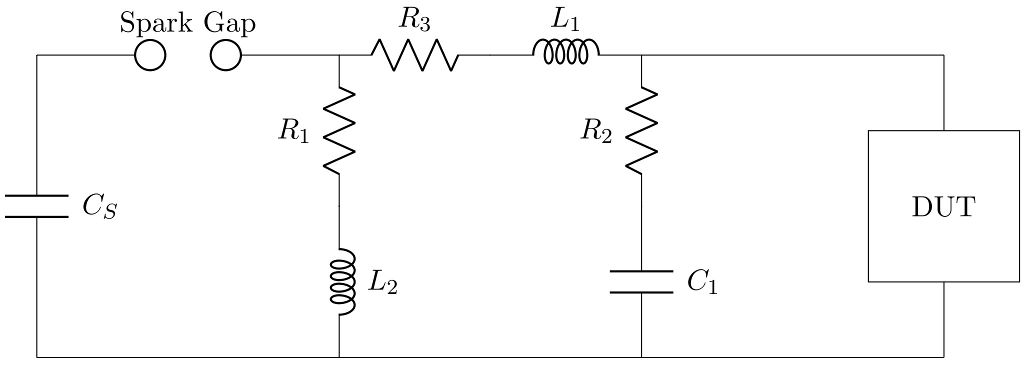

Figure B.1: 8/20 μs impulse generator used in laboratory experiment

Appendix C

ICLP Paper on Resin

C.1 Preface

The following appendix is a conference paper titled: **Preliminary Investigation into the Interaction between Lightning Current and Resin**. It was presented at the *International Conference on Lightning Protection (ICLP)* held in October 2014, Shanghai, China.

C.2 Overview

The paper is an overview of an investigation into the reaction of *Pinus Elliottii* (Slash Pine) resin when an impulse is applied to a small sample. The resin has a very high breakdown strength and would not flash over when 20 kV was applied over a 0.5 mm gap.

Preliminary Investigation into the Interaction between Lightning Current and Resin

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***Abstract*— An introductory experiment is undertaken which investigates the interaction of the resin of a *Pinus Elliottii* (Slash Pine) and an impulse response. A resonance is seen in the resulting current waveforms with maximum current amplitudes of around 440A for an impulse charged to 18kV peak voltage. The resin is found to have a high breakdown strength and no heat or damage is observed when the current passes through the test sample. While laboratory generated impulses cannot confirm what is seen in the field when a natural lightning attachment occurs to a tree, it could give a better indication of what could be expected. More tests are needed to confirm the preliminary results seen.**

Lightning effects;Applied Impulse; Pinus Elliottii; Slash Pine Resin.

I. Introduction

Lightning research pertaining to human civilization, which includes lightning interaction with biological conduits such as humans and plants is of particular interest. The interaction between lightning and trees has been investigated since before the 1960's, most notably by AR Taylor [1,2,3]. An attempt has been made to see whether any correlation exists between factors of a tree, such as form or age, and the damage the tree sustains from an attachment [2]. While some valuable conclusions were drawn about the percentage of bark loss in relation to tree size, but the lightning current delivered to the tree was not recorded.

Using an impulse current waveform produced in the laboratory, the factors within a tree can be isolated and controlled, thereby making a direct comparison with each attribute and current density; However, since the interaction of lightning and the resin of a tree has not been studied, this is the only constituent of the tree which will be investigated in this paper. The resin is hypothesized to play a role in the explosive force which is a result of lightning acting on a tree. Since these expulsions of wood projectiles are potentially deadly, the risks of planting certain types of trees would be worthwhile knowing [4]. Current risk assessment can include the size and shape of a tree, but not this explosive nature [5]. This implies that if a direct relationship exists between the resinous content of a tree and the most likely result of a strike to it, it could be included in future procedures, for example the safety warning for a plantation of this tree type could be raised earlier, or if it is likely to ignite, fire control could patrol these tree types more actively.

II. Background

Previously the current strength was assumed to be directly proportional to the pressure produced in a lightning attachment to a tree, which was then responsible for the damage, but Taylor concludes that the evidence in his study contradicts this and that there is some careful balance between tree factors, such as age and moisture content and the current discharge that dictates the amount of damage seen on a tree [2].

Four generic categories exist which define the layers within a tree: heartwood, sapwood, cambium and the bark [6]. Each layer carries different nutrients which will affect the electrical resistance of the layer. In the heartwood in the center of a tree no water transport takes place, the sapwood that surrounds it contains most ducts that carry water and nutrients reducing its impedance. The cambium has the most active transport of nutrients and production of cells which would make this the path of least resistance, but this layer is very thin. The effect resin would have on the path of lightning and the impedance in the various layers has not yet been studied. The AC (60Hz) resistance of live trees has been measured indicating different values for two tree types and showing a negative thermal coefficient; However, this measurement did not include a measurement for impedance at higher frequencies [7]. As it is likely that the conductivity will change, similarly to the soil as in [8], this only gives a general idea of how the lightning will interact with the tree.

In South Africa, three main genera of invader trees are planted for wood uses by a major forestry company[1]: *Pinus*, *Acacia* and *Eucalyptus* [9]. These are of main concern as these are the species that are most likely struck. Concentrating on the former, one tree constituent unique to the *Pinaceae* family is isolated and analysed, namely the resin. As the trees are biological and grow dynamically, it is highly likely that the resin will not be identical, even though it is only one isolated constituent. These tests are performed as a preliminary investigation on the rough effect resin will have on the pine tree and not a quantifiable estimation. Within the species of *Pinus* there is a variation in the constituents of the resin, so a further specialisation is made to exclude species not grown widely. Three are chosen as an initial test group: *Elliottii*, *Greggii* and *Patula*.

[1] Mondi Ltd uses the majority of the wood for pulping purposes and not resin collection.

A. Resin

The resin channels or ducts occur mainly longitudinally in trees but are interconnected by smaller transverse paths. They are present from just beneath the cambium throughout the sapwood and lessen to the heartwood [10].

When an attachment to a tree has occurred in the right conditions, the current path can be seen indirectly after the event through a deep fissure along the tree bole which either seems to follow the vertical or spiral pattern. If the path followed by the current is along the edge of the tree bole and not in the center or within the tree, there are resin ducts present just beneath the cambium so even if no electrical interaction is taking place, there is a thermal effect due to the proximity to the current channel. In a previous experiment, wood sections were subjected to a DC current flow [11], demonstrating that the current is more likely to follow the grain of the wood rather than across it. This is also supported by electrical resistivity measurements previously taken in another experiment, in which the radial resistance is far greater than the longitudinal [7]. However, these experiments were not done using impulse currents, nor were they performed on trees which had resin.

The temperature affects the properties of the resin and the long duration of the harvesting method explained in detail in section III means the resin samples are exposed to air, sunlight and fluctuations in temperature. This could change the dielectric properties that resin has when it is within a live tree. The moisture content varies very slowly and is a small amount of the resin (2%) [12].

The composition of resin can be generically divided into the volatile components (monoterpenes and sesquiterpenes) and the rosin or resin acid components. Each species varies quite significantly and the location has a large effect on the percentile composition but the genes will dictate the presence of chemical elements [13]. The monoterpenes are alpha-pinene and beta-pinene, so named because of their abundance in pine trees. These volatiles have 20-50% each in an *Elliottii* tree. The pinenes have a low flash point, the temperature at which it vapourises and it is possibly why the current could cause a pressure wave or explosion through the resin as they are major components [13]. The main resin acid is Levopimaric acid (38%), which has a high boiling and flash point [14], keeping the volatiles in a certain location within the resin.

B. Electrical Experiment Approach

A set variable is altered in a simulated condition and the damage is measured to check for correlation. This is easier to do than testing the real results in the field, such as in Mäkelä's experiment since the data is not generated with the experimenter controlling the variables [12]. However, using this method cannot account for the exact conditions present when a natural attachment to a tree occurs. A natural lightning attachment, as well as having far larger energy and current values would also have multiple strokes and other disturbances in the air before interaction with the tree.

A combination impulse generator applies an impulse voltage to a test sample and provided there is breakdown current will flow through the sample. In the case of lightning attachment to a tree, a current has already been established through the air, but the combination impulse generator will allow for both current and voltage across the sample. The occurrence of lightning can be seen on both a macroscopic and microscopic level [15], but the damage in this experiment will be measured with the naked eye. When a biological structure is struck, a non uniform field is created, which is what the rod/plane exhibits and why it will be used in this case.

III. Resin Collection

"Fig. 1" illustrates the method used to collect resin from a pine tree. This method is explained further in subsection A and subsection B discusses the results of the collection.

Figure 1. Resin Harvesting Method

A. Harvest Setup and Method

Three methods are currently common practice to collect resin from pine trees, the herringbone, bark chipping and wood chipping method. As the first priority is not to damage the tree, the herringbone method was used as no acid needs to be applied to the tree and it leaves a smaller amount of scaring. The resin was obtained by removing a section of bark along the tree bole which was a minimum of 10cm wide and 25cm long

The cambium was completely removed and diagonal cuts were made forming a Vee pattern, which can be seen in "Fig 1". These cuts are made to sever the resin ducts present in the sapwood and then form a channel for the resin to follow as it flows downwards. A bottle is attached using a wire bound around the tree at the bottom of the bare section where the vee forms a neck.

B. Collection Results and Discussion

Table 1 shows the volumes of resin after harvesting from three different species. The resin was collected a month after the process was started and the bottles affixed. Very little of the material was present from each tree, which is the main limiting factor and only one species is tested initially. Collection was done during the winter months with the average temperature being low and not conducive to resin flow, which means the summer months would have a better yield.

TABLE I. RESIN VOLUMES FROM THREE SPECIES AFTER A MONTH

Sample	*Pinus Elliottii* *(mm^3)*	*Pinus Patula* *(mm^3)*	*Pinus Greggii* *(mm^3)*
1	14137.17	4948	353.43
2	3534	706.86	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	-
7	0	0	-

IV. EXPERIMENTAL SETUP

In "Fig. 2" , the electrical set up is illustrated: The impulse generator is connected at the points on the sample where the impulse is applied.

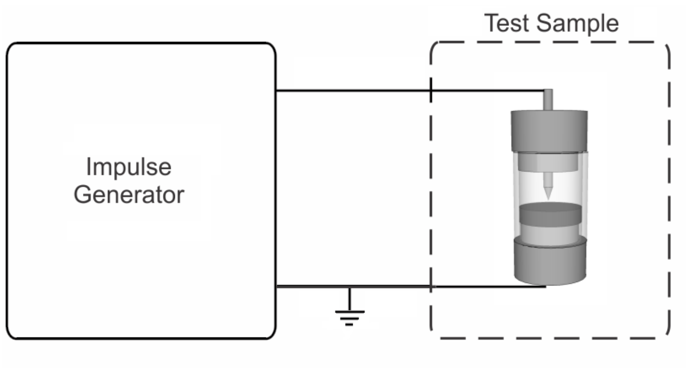

Figure 2. Electrical Set Up of Impulse Generator and Resin Test Capsule

"Fig. 3" shows the expected current waveform for a short circuit test from the 8/20µs impulse generator which is used. The generator applies a standard lightning impulse to the sample and the waveshaping components then produce a current waveform with 8µs rise time and 20µs time to half. The capacitors in an impulse generator are charged to a set voltage and that voltage is the peak voltage in the impulse that is applied to the sample.

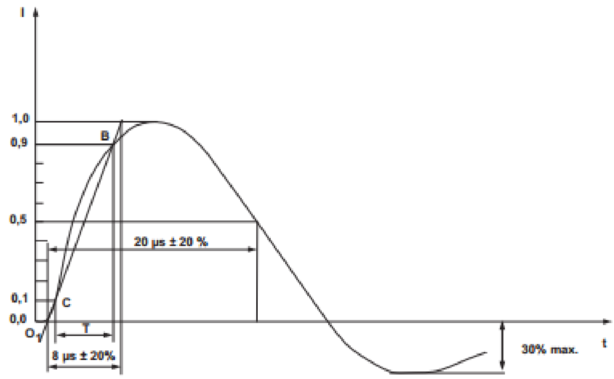

Figure 3. IEC61000-4-5 Standard Waveform for 8/20us Short Circuit Current

"Fig. 4" shows the cylindrical acrylic container used to keep the resin in the desired position. It has an inner diameter of 18mm and a height of 5cm. A modified brass screw is fixed to the bottom of the cylinder through threading, by which the contact of the impulse generator can be attached. Another altered brass screw is attached to the top of the cylinder, with a pointed rod through the center to form a rod plane set up. The top end of the cylinder is not tightly fixed to allow the pressure to escape rather than damage the container and allow resin to leak. Height A in the figure depicts the height between the tip of the rod and the base of the plug, which is the distance the impulse is applied to, while height B depicts the height the resin was filled to in the cylinder. Both of these heights can be varied.

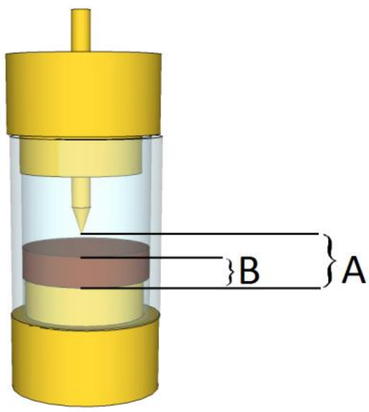

Figure 4. Resin Test Capsule (A - Breakdown Gap, B - Resin Height)

V. METHODOLOGY

Table 2 shows the heights and gap distances set for test 1 and test 2, while the following procedure is performed in both. tests The fluctuation in pressure is considered negligible. Temperature and moisture content are kept constant, along with the volume and the surface area of the resin. The resin is extracted from a *Pinus Elliottii* tree located at S26°48'24" E30°29'56", approximately 18 years old.

TABLE II: GAP DISTANCE AND HEIGHT SETTINGS FOR TEST 1 AND TEST 2

	Gap Distance A (Applied Gap)	*Height B (Resin Height)*
Test 1	2mm	3mm (763 mm^3)
Test 2	0.5mm	2mm (509mm^3)

Voltage impulses of increasing peak value (2kV to 20kV in steps of 2kV) are applied to the sample. The current and breakdown status of the resin is recorded along with pressure and temperature of the environment. After each discharge the capsule is measured for any difference in temperature or viscosity. A qualitative assessment is made of the temperature difference and viscosity as the temperature difference is measured by touch and the viscosity is measured by turning the capsule horizontal and checking by eye if the viscosity has changed notably. Similarly to the experiment performed by Hirano, if any damage is observed then the length, width and depth is recorded [16]. The same sample is used for multiple firings owing only to the shortage in the material. Certain voltage values (12kV and 18kV) are repeated to confirm the waveform followed the same pattern and that any chemical change that occurred in the sample had no short term effects.

VI. RESULTS AND DISCUSSION

Table 3 shows the results of the qualitative observation. There was no change in any of the observations except for an increase in viscosity in test 2, which occurred at 10kV peak voltage and higher. However, the noticeable increase in viscosity grew less and less as the applied voltage was increased. This could indicate that the nonaqueous components, the volatile terpenes, are being broken down and diffused into the air.

TABLE III. OBSERVATION RESULTS FROM TEST 1 AND TEST 2

Observation	*Test 1*	*Test 2*
Heat	None	None
Viscosity	None	Increased
Flashover	None	None
Damage	None	None

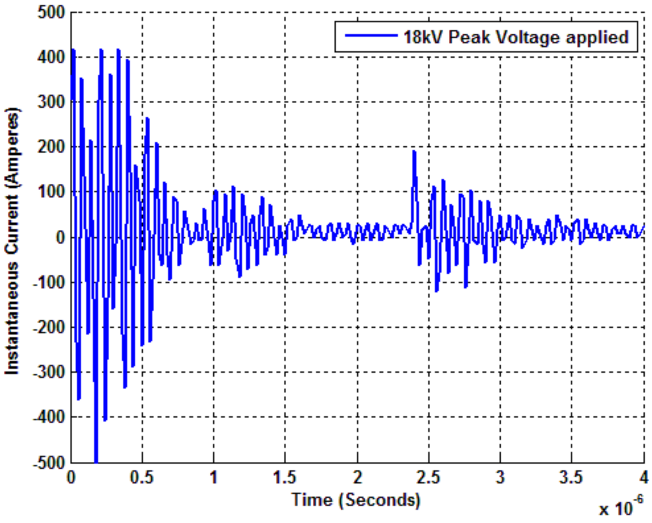

Figure 5: Time versus Instantaneous Current for 18kV Peak Voltage Applied (Similar for All Applied Voltages)

While breakdown of the resin did not occur, some leakage currents were observed. The current waveforms for 18kV peak applied voltage is displayed in "Fig. 5". The current waveforms for all peak voltages that were applied follow a similar pattern. A Fourier transform is generated in software using the Fast Fourier Transform method on each of the impulse waveforms, the result of which can be seen in "Fig. 6" for 18kV peak applied voltage. There are peaks at around 10MHz and 15MHz which all of the current waveforms have from each different voltage firing values.

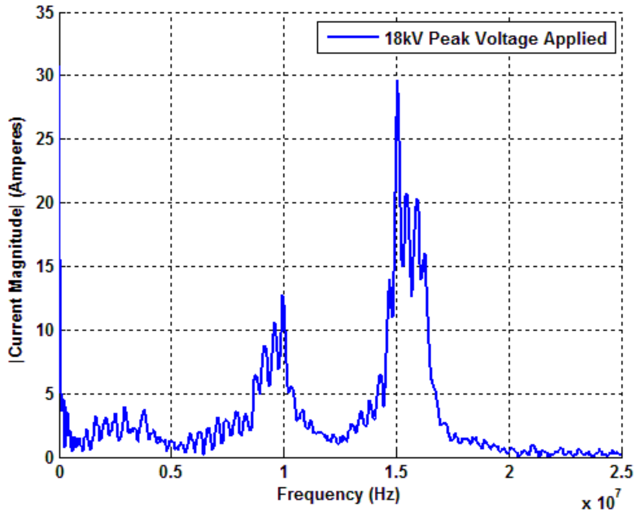

Figure 6: Frequency versus Current Magnitude 18kV peak voltage applied (Similar for All Applied Voltages)

One proposed explanation is that the volatile elements, such as the Pinene that have a low flash point, are vapourised as the first current channel occurs (seen as a decaying peak with noise), the surrounding volatiles then fill the void which allows the second discharge through the sample, which has a smaller magnitude. This process then continues until the energy is completely discharged. The faster harmonics seen as ringing in "Fig. 4" are assumed to be either switching artifacts from the impulse generator or the resonant frequency seen in "Fig. 5" around 15MHz from the interaction of the resin and the circuitry in the impulse generator. The preliminary results indicate that the dielectric strength of resin is very large as it did not allow for a complete breakdown and that it also has some degree of impedance as there are certain frequencies that are more amplified than others.

VII. Future Experimentation

First another sample from another individual of the same species and age will be tested using the same procedure to check the amount of variance between trees. Next the interspecies variance will be tested between a *Pinus Patula* and a *Pinus Elliottii* . The effect of age will also be measured on a *Pinus Elliotti* by using a 5 year old tree resin sample.

A frequency response test should be done to check if there are any harmonics in the lightning impulse that the resin is amplifying without the equipment interference. To confirm that the resin acids are responsible for the energy storage, impulses will be tested similarly on a sample of a pure resin acid. The gap and surface area exposed to air will also be varied to test if the volatiles need to decompose to air or if this constriction causes an explosion.

As this research is part of a larger whole, how the lightning interacts with the entire tree a few heat tests will be performed on the resin as well. Because the channel burns the surrounding cells or vapourises the fluid as the lightning courses through the tree, it is hypothesised that even if the lightning does not travel directly through the resin, the heating from the nearby channel will have an effect on the trees system. The heating occurs as the wood is wet, which means the dielectric power factor is poor, causing more energy to be dissipated as heat [17]. This could also potentially be the reason the resin might explode.

VIII. Conclusion

This initial experiment is merely the beginning of the extension of the research that has already been done regarding the interaction of trees and lightning, but the first experiment done in regard to resin and lightning. Varying peak voltages have been applied with an impulse waveform and the temperature and viscosity recorded. An explanation is proposed as to the properties of resin from a *Pinus Elliotti* tree based on the results this preliminary study, this includes indications that resin from this tree has a high breakdown strength. However, more tests will be needed to confirm the energy storage and flammable capabilities and the exact interaction of lightning and resin.

Acknowledgment

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Appendix D

Further Ground Investigations

D.1 Preface

The following appendix is an extension of the investigation to estimate the value of the air portion of the model being part of the ground terminal.

D.2 Overview

The two set-ups were compared using a 2 m long cylinder with a diameter of 0.3 m and the waveform was applied as a surface terminal to the top of the wood material. These values were chosen as it is long enough to allow for fringing of the electric field and it is close to the size of a pine tree bole.

The current density can be evaluated directly at a point by plotting the fluctuations at a certain point over time. However, since the current density is a vector and the bulk of the magnitude is in the z-direction, it is easier conceptually to compare only one direction, in this case the z-direction and using the mid-point of the wood cylinder. this can be seen in *Figure D.1*.

The current can be found and compared for both models (smaller and larger ground terminal) by choosing a surface perpendicular and within the wood dielectric cylinder and integrating the current density. *Figure D.3* illustrates the directionality of the current density vectors and the middle horizontal line indicates the surface chosen. However, it must be kept in mind that the current will most likely not be the same across all surfaces chosen along the length of the cylinder as the current density is not identical.

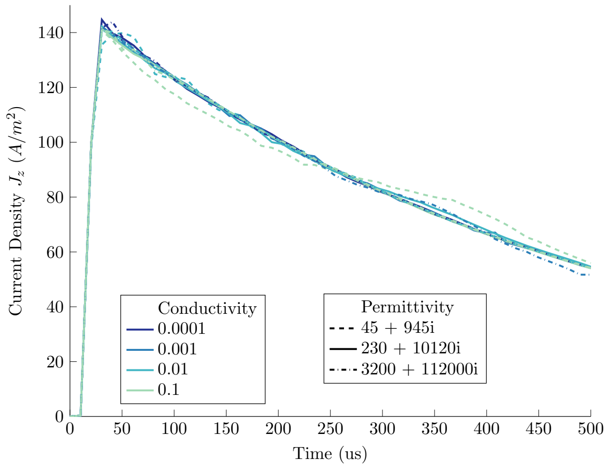


Figure D.1: Current density at mid-point of wood with air and wood ground plane

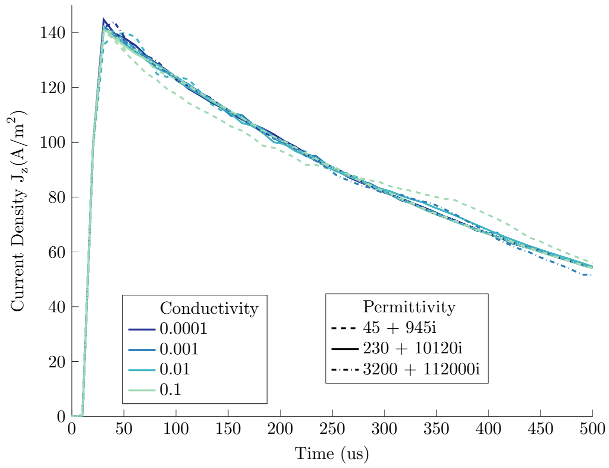


Figure D.2: Current density at mid-point of wood with wood ground plane only

When comparing the graphs of the instantaneous real current for both the large and small ground terminals in *Figure D.4* and *Figure D.5* respectively, there is a slight difference visible in the magnitude. Here it is clear that the model performs as expected, in that the instantaneous real current follows the applied waveform closely. The reason for the deviation is that the air is considered, so a boundary exists between the wood and air and some losses can occur, including resistive losses as expounded upon later. In a separate test, the wood cylinder was evaluated without the surrounding air cylinder to confirm this.

The difference in the instantaneous real currents is 350 A at most at the 50 µs time mark with a permittivity value of $3200 + j112000$ and $0.0001\,\mathrm{S\,m^{-1}}$ conductivity value, seen in *Figure D.6*. While 350 A is a small number as compared to the values of the applied current at that point in time, the difference is still considered significant and might be compounded in further investigations. It is therefore more accurate to use the larger ground plane as this more closely resembles the natural setup of a lightning to tree attachment.

Another way of comparing the two situations (large and small ground plane) is by evaluating the resistive power loss as mentioned. This is done by integrating the vector current density multiplied by the vector electric field over the entire volume of the wood cylinder. The instantaneous resistive power losses are plotted for the smaller and larger ground plane in *Figure D.8 and D.7* respectively.

These graphs show that the power loss for both situations have similar shapes, but the magnitudes are different. As the same material and volumes are being used, this is to be expected. The higher losses occur in the wood with the smaller ground plane as there is less allowance for the losses to occur in the air as there is with a larger ground plane.

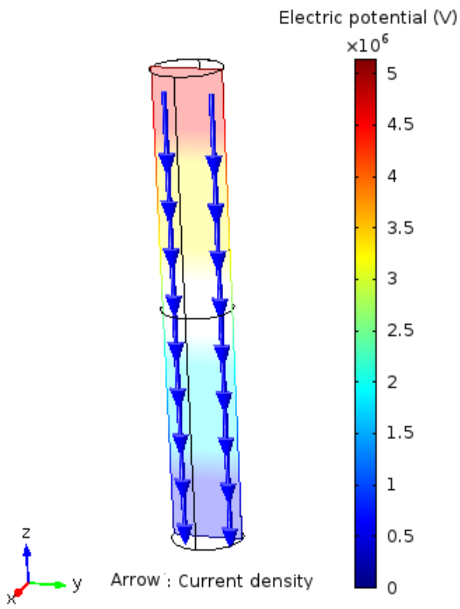


Figure D.3: Current density (arrows) and electric potential (colourbar) for the wood cylinder - larger ground terminal

Once again the difference can be seen in *Figure D.9* more clearly. here the significance of the different ground planes seems much less, as it is mainly the smaller permittivity valued data that shows any difference.

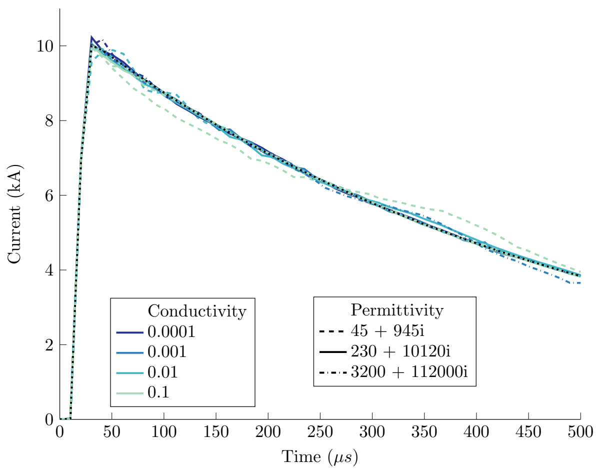


Figure D.4: current through wood with air and wood ground plane

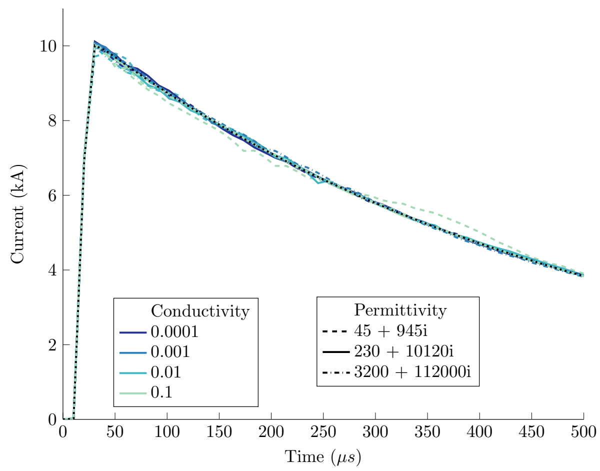


Figure D.5: current through wood with wood ground plane only

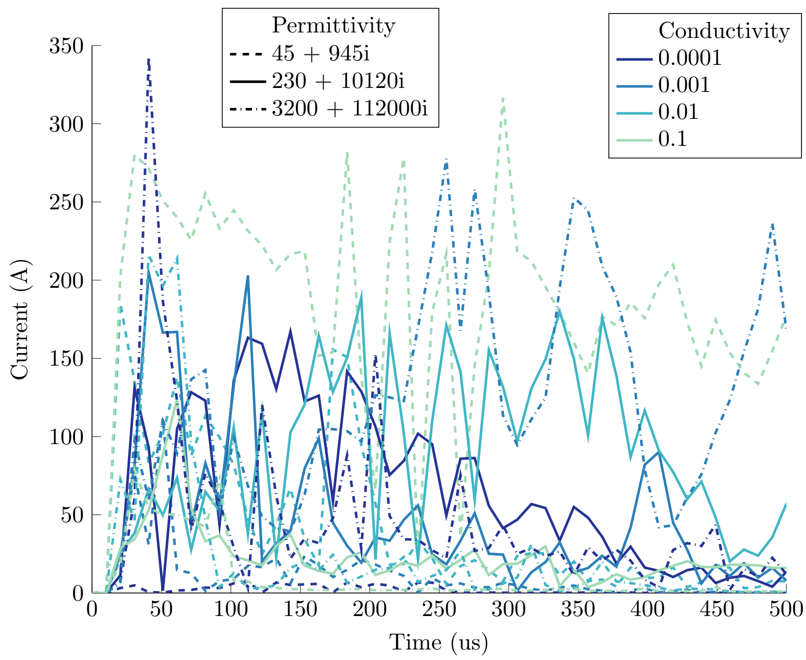


Figure D.6: difference in current through wood with smaller and larger ground plane

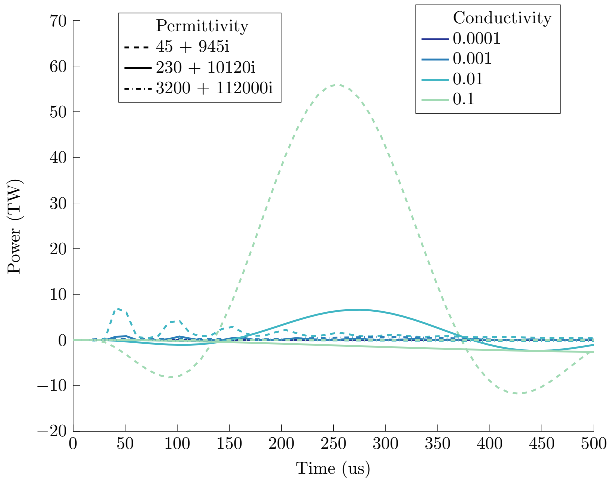


Figure D.7: power through wood with larger ground

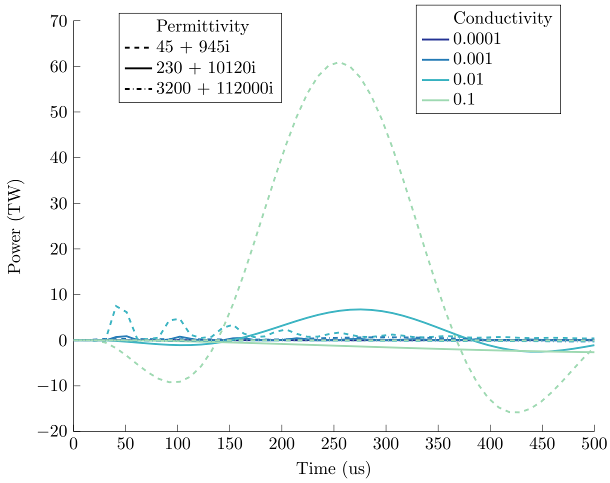


Figure D.8: power through wood with smaller ground

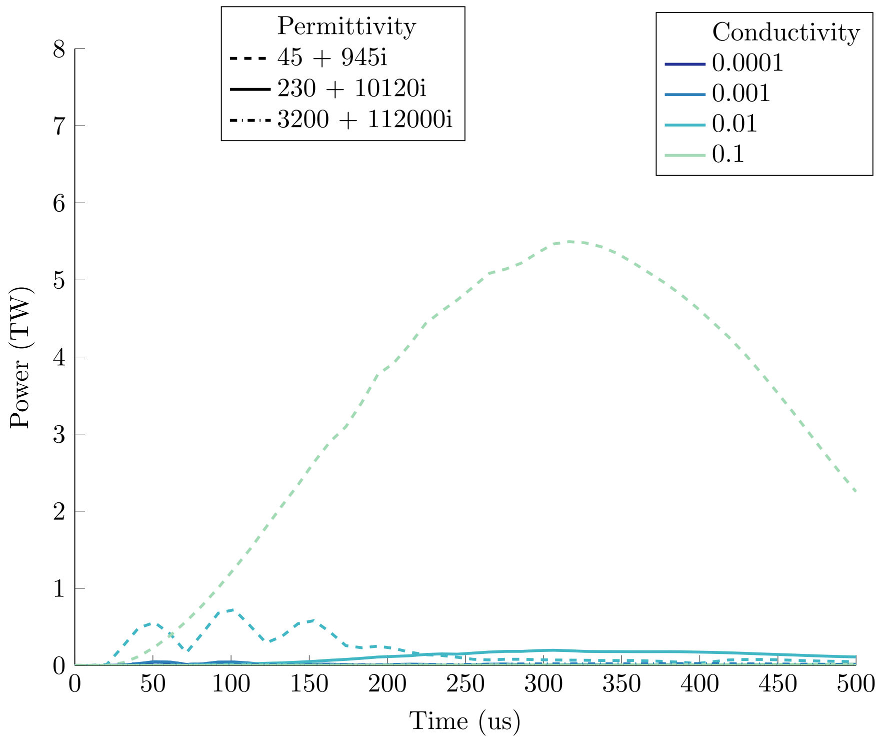


Figure D.9: difference in instantaneous power through wood with smaller and larger ground plane

Appendix E

Currents Case B: External Water Channel

E.1 Preface

The following appendix is presents all the current waveforms for water and wood in Case B: External water channel.

E.2 Overview

The currents for Case B: External water channel are displayed in the following three figures. Each figure represents a different permittivity value for the wood and shows the current through water and wood by the line type.

These graphs follow those of Case A: Internal water channel quite closely, presenting the same behaviour of the wood and water. Only the larger permittivity values show an exchange in current between the water and wood channel.

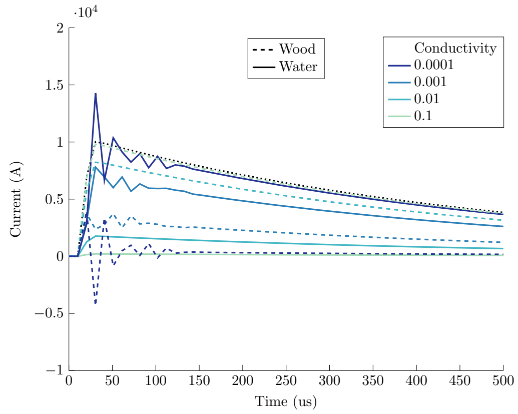


Figure E.1: Case B: Current through water and wood - Permittivity 45 + 945j

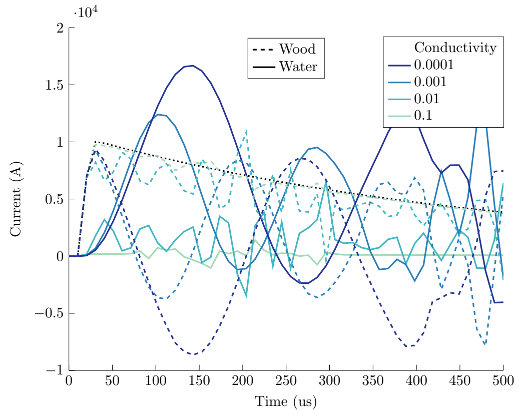


Figure E.2: Case B: Current through water and wood - Permittivity 230 + 10120j

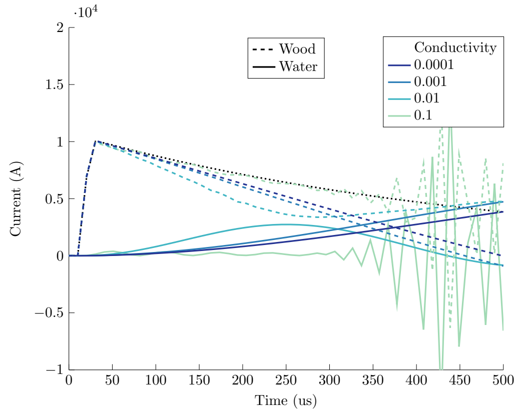


Figure E.3: Case B: Current through water and wood - Permittivity 3200 + 112000j

Appendix F

Placement of Integration Surface

F.1 Preface

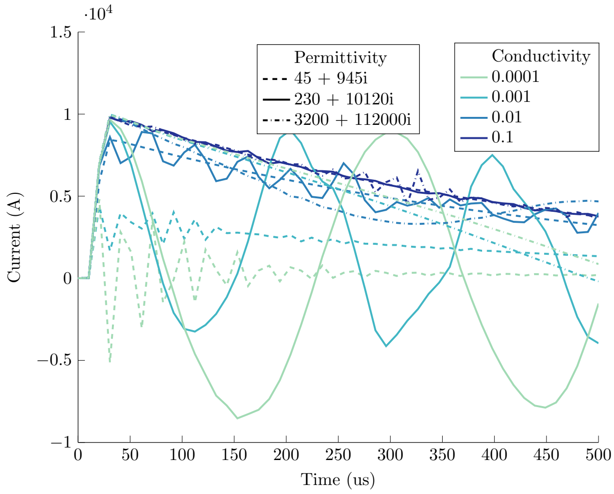
The following appendix presents the results for a simulation performed to confirm that the placement of the integration surface along the channel is insignificant.

F.2 Overview

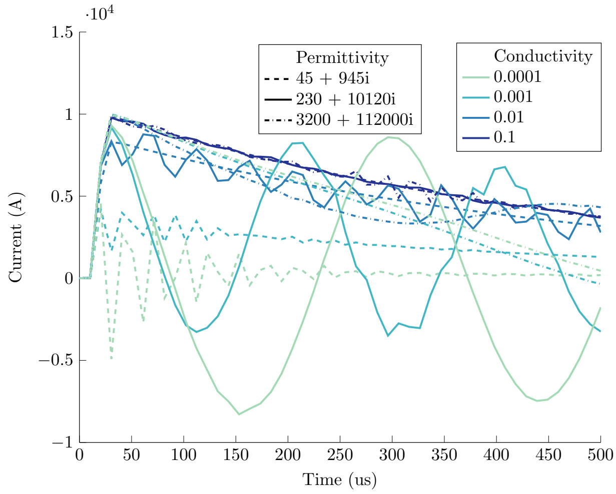
Similar to Case B: An external water channel along a wood cylinder was simulated and the current obtained through integration of the cross sectional surface.

However, the surface was chosen at increasing distances from the source. As can be seen from the figures that follow, there is no significant difference in the currents, and the overarching behaviour can easily be seen. While there might be slight differences in the current density that result in the slight fluctuations, the current is very similar for each integration surface.

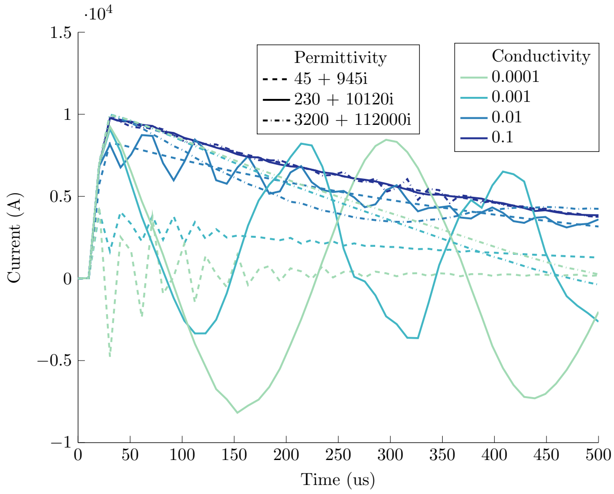
This implies that the current is increasing and decreasing sinusoidally consistently in the entire cylinder at the same time, so the sinusoidal behaviour is not likely from reflections.



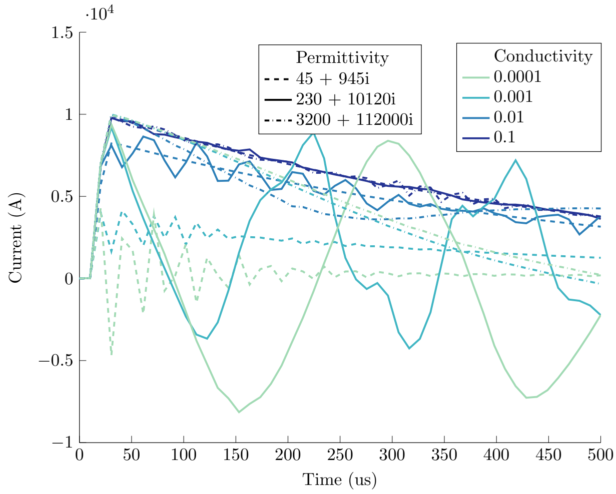
(a) 0.1m from the source



(b) 0.2m from the source



(c) 0.3m from the source



(d) 0.4m from the source

Figure F.1: Current through wood for various integration surfaces

Appendix G

Currents Case C: Internal and External Water Channel

G.1 Preface

The following appendix is presents all the current waveforms for water and wood in Case C: Internal and external water channel.

G.2 Overview

The currents for Case C, both water channels are displayed in the following three figures. Each figure represents a different permittivity value for the wood and shows the current through water and wood by the line type.

Case A to B all have similar water and wood volumes and therefore did not show any significant difference in the graphs. The numerical modelling errors are apparent as large fast changing fluctuations in the graphs.

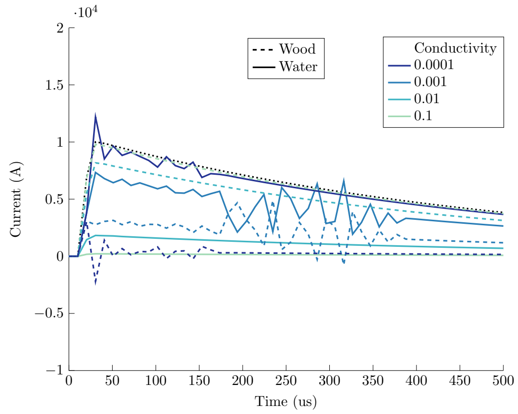


Figure G.1: Case C: Current through water and wood - Permittivity 45 + 945j

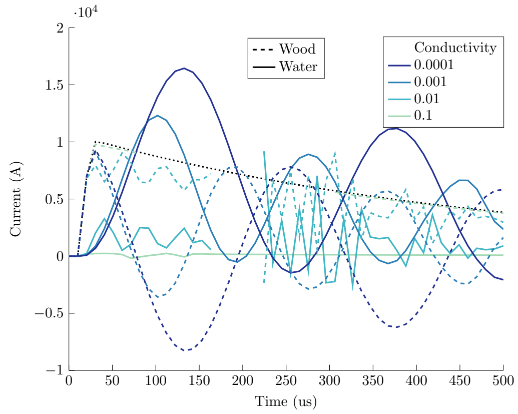


Figure G.2: Case C: Current through water and wood - Permittivity 230 + 10120j

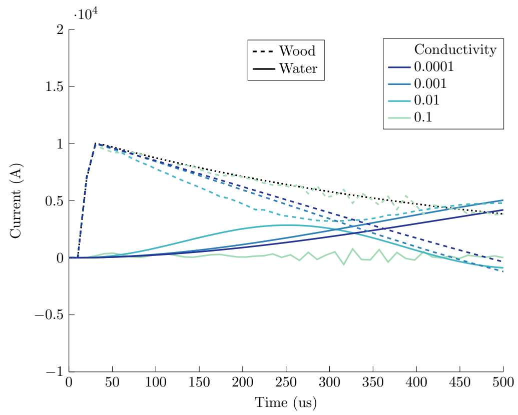


Figure G.3: Case C: Current through water and wood - Permittivity 3200 + 112000j