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Electrical Measurement of Root Mass and Root Location

by Tim Ellis, Kristen Feher, Wayne Murray, Keryn Paul, Jim Brophy, Kris Jacobsen, Vijay Koul, Peter Leppert, and John Smith

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Researcher Contact Details

Tim Ellis
CSIRO Land and Water, Box 1666 Canberra 2601

Phone: +61 -2 6246 5743
Fax: +61 -2 6246 5800
Email: tim.ellis@csiro.au

In submitting this report, the researcher has agreed to RIRDC publishing this material in its edited form.

RIRDC Contact Details

Rural Industries Research and Development Corporation
Level 2, 15 National Circuit
BARTON ACT 2600
PO Box 4776
KINGSTON ACT 2604

Phone: 02 6271 4100
Fax: 02 6271 4199
Email: rirdc@rirdc.gov.au.
Web: <http://www.rirdc.gov.au>

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Foreword

The measurement of the depth, lateral extension and density of plant roots is often of interest in crop research, forestry and agroforestry as roots are vital to the survival and growth of plants, and the water balance of landscapes. The mass of roots, particularly in forests, also represents a significant proportion of the sequestered carbon, the magnitude of which is of interest for carbon accounting. This report describes 1) the evaluation of low frequency (kHz range) electrical capacitance measurements of the roots of Australian forest eucalypts and; 2) progress towards the detection of roots within a soil medium, using high frequency (MHz range) electrical measurements. It shows that capacitance measurements can be related to the root mass of forest trees; and b) it is possible for roots to act as antennas within a soil medium - their associated electromagnetic fields can be detected remotely, over short distances (~ 1 metre).

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Peter O'Brien

Managing Director

Rural Industries Research and Development Corporation

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Abbreviations

Symbol	Description and units
$\bar{k}$	Wave number of a material, m^{-1}
$\bar{\epsilon}$	Permittivity, Fm^{-1}
BM_{ag}	Above ground biomass, Mg ha^{-1}
C	Capacitance, F
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFF	Department of Agriculture, Fisheries and Forestry
E	Electric field
H	Magnetic field
M	Root mass, kg
PVC	Poly vinyl chloride
$R_{<2}$	Proportion of root biomass < 2 mm diameter
X	Input signal, V
X_{db}	Attenuation, db
X_o	Input signal, V
Z_r	Impedance, Ω
μ	Permeability of free space; $4\pi \times 10^{-6} \text{ Wb/A/m}$
ω	Frequency, Hz

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Executive Summary

What the report is about

This report investigates two electrical methods for the measurement of roots, which have previously shown promise for the development of rapid non-destructive techniques for use by researchers or plant breeders. We show that: 1) low frequency (kHz range) capacitance measurements can be indicative of the mass and length of the root systems of eucalypts; and 2) roots can transmit detectable high frequency (MHz range) signals over short distances (~ 1 metre). The use of the latter, however, appears limited by the relative electromagnetic properties of soil and roots.

Intended audience

This report is relevant to forestry, agroforestry and plant breeding researchers, in projects where root mass and root location are measured.

Background

The first method of low frequency (low MHz range) capacitance measurement, has been known for several decades to provide an easy comparison of root system 'size', and is understood to be directly related to root mass and root length. This method has traditionally been applied to herbaceous crop and pasture species; here we evaluate the method on plantation eucalypts as there was interest in measuring below ground forest biomass to determine carbon sequestration.

The second method described here involves the use of high frequency (low MHz range), whereby roots tend to transmit signals along their length. These signals have been shown to be remotely detectable and thereby potentially useful for the non-destructive measurement of the spatial location of roots. For example, because some water use characteristics of plants are related to rooting depth, a rapid estimate of maximum depth is useful to water balance modellers and plant breeders selecting high water use cultivars that could reduce deep drainage. A second need for such a method often arises in agroforestry research, where it can be useful to measure the lateral extent of roots from trees which compete with adjacent crops and pastures.

Aims

1. To evaluate the low frequency electrical capacitance method for the measurement of tree root mass and root length;
2. To determine the governing principles and limits for the transmission of electromagnetic signals through a root system;

Methods

To address Aim (1), we made capacitance measurements on plantation eucalypts prior to their destructive sampling for the measurement of below ground biomass (undertaken by another project funded by DAFF). To Address Aim (2), we undertook 2 laboratory experiments to a) measure the attenuation (signal loss) along a length of root embedded in sand; and b) measured the dielectric properties of sand, loam and root materials for use with antenna theory to allow interpretation of (a) and an understanding of the likely limits to signal propagation in roots.

Key results

Low Frequency Capacitance - we provide the first published evidence known to us, that low frequency capacitance C measurements can be related to root mass and, possibly, to root length of plantation eucalypts. Trees at 3 mature plantation sites produced similar relationships between C and root mass. The one younger site showed a different relationship between C and root mass, but the

results from the 4 sites produced a relatively unified relationship between C and root length, although the latter was inferred and not directly measured. This is consistent with root capacitance theory. It is likely that the younger site had a greater proportion of fine (<2mm diameter) roots and therefore a greater total root length.

High Frequency Measurement of Root Location - signals can be transmitted from plant stems to roots, which tend to act as underground antennas, emitting electromagnetic fields which can be detected remotely. However, it appears that the relative dielectric properties of roots and soils are such that signals will travel only relatively short distances (2 to 3 m) along large diameter (10 to 20 mm) roots, before becoming too small to detect.

Implications

These results are relevant to researchers of plant root systems and we have identified some theoretical and practical limits of electrical measurement. In this preliminary project, however, we were unable to develop the methods to a point that they are likely to be directly useful to the agricultural and forest industries.

Recommendations

Our recommendations relate to root research and geophysical research:

1. Since the destructive measurement of tree roots is typically a laborious and expensive process, electrical capacitance measurements should be routinely considered for preliminary investigations as they are rapid, easily performed and could augment other sampling methods. Interpretation of results should include consideration of differences in age of the trees, and hence differences in the proportion of fine roots and total root length;
2. Our preliminary results suggest the high frequency method is unlikely to provide a ready path toward the development of routine methods for the location of roots in soil. However, because our investigations were not exhaustive, we suggest that root researchers and geophysicists keep in mind the possibility that a greater efficacy in this technique may be realised through further investigation in the future.

Introduction

The position and density of plant roots is of critical importance to water and nutrient uptake, plant growth and reproduction. The maximum depth and lateral extent of roots typically have significant effects on the water balance of a landscape (e.g. deep drainage) and competition between species e.g. agroforestry trees growing adjacent to crops or pastures. Many research areas require information about plant roots. Sampling and measuring plant roots is difficult and is typically undertaken by destructive sampling (e.g. soil cores) and laboratory techniques for washing, scanning and determination of mass and length. Significant advances in image analysis technology have greatly improved the dimensional measurement of cleaned root samples. However, although several non-destructive methods for root measurement have been developed (e.g. rhizotrons), by far the most commonly used method for root research is destructive sampling. Since the 1970s, the electrical capacitance of roots has been known to be related to root mass and length (Chloupek, 1972). Dalton (1995) offered an electrical model for the observed relationship between electrical capacitance (C) and root length, hypothesising that roots acted as cylindrical capacitors and therefore their capacitance was more or less proportional to the length of a root. A branched root system is analogous to capacitors arranged as a parallel circuit and, therefore, the total capacitance of the root system is the arithmetic sum of all the individual capacitances. This historical capacitance work was principally restricted to crop and pasture species and much of the work was undertaken in the laboratory. In previous work we showed the likelihood that capacitance measurements could also be related to the root mass of trees in the field (Ellis *et al.*, 2008), however resources did not allow corroboration of this by destructive sampling.

Electrical capacitance measurements provide no information on the spatial distribution of roots. In our previous work (Ellis *et al.*, 2008) we showed that high frequency methods can be used to non-destructively locate individual roots, and was possibly related to root density. This was also novel work, and although at a very preliminary stage, suggested that a non-destructive method could be developed for locating the lateral extent, and possibly the maximum depth of roots.

This report is divided into two main sections. Firstly, under Low Frequency Capacitance Measurements, we corroborate that electrical capacitance can be related to root mass on destructively sampled plantation trees. We show that low frequency capacitance was proportional to total root mass at four different sites. Mature trees at three sites showed similar relationships, however younger trees followed a very different trend. This appeared to be due to the greater proportion of fine roots ($< 2\text{mm}$ diameter) at the younger site, and therefore the greater root length. Secondly, under High Frequency Location of Roots, we propose and test the hypothesis that roots will act as underground antennas. Laboratory experiments are used to explain previous measurements of signal transmission along lateral tree roots. We conclude that, although non-destructive detection of roots is possible by this method, it appears that losses are so high that it would be unlikely that useful signals would be transmitted many metres, especially in small diameter roots. We discuss these results with respect to the potential for developing more routine electrical methods for non-destructive root measurement. A final section briefly outlines implications and key recommendations of the research.

Low frequency capacitance measurements

Introduction

Low frequency (kHz range) measurements of electrical capacitance C have been shown to be related to the 'size' (e.g. mass) of plants' root systems (Chloupek, 1972). Although the electromagnetic theory of this measurement, and an exact electrical analogy of the stem-root-soil continuum is not well understood, Dalton (1995) presented a (now) popular model, which assumes a plant root to be a cylindrical capacitor. In the Dalton model, C is proportional to root length, for a constant diameter root. Because of geometric and allometric relationships, however, the Dalton model also allows that C can be related to root mass. Most published work on the electrical capacitance of root systems has been restricted to herbaceous annual crop and pasture species, which has a relatively small range of root diameters. In this experiment, we test the hypothesis that C is also related to the root mass of plantation trees, which have woody roots and a larger range of root diameters.

Methods

At low frequencies (kHz range) root systems act as capacitances when a circuit is made between the soil (ground) and the tree stem. For a detailed description of the theory and methods used for the electrical capacitance measurements on trees, see Ellis *et al.* (2008). Briefly, metal probes were placed in the tree stems and the soil and the circuit was completed with a portable 4 terminal impedance meter. This measured the electrical capacitance C , in Farads (F) of the tree root system at a frequency of 1 kHz. We showed the potential advantage of using a 4-terminal method (i.e. 2 terminals placed in both the tree stem and the soil) for a more accurate measurement of C , as this eliminated impedances, which were particularly high with the stem probes. Our preliminary work showed that the method was highly repeatable and, as with other work on herbaceous species, C was independent of the lateral position of the soil probes, relative to the stem of the tree. In addition, there was a relationship between C and stem diameter (Figure 1). This was an encouraging sign that C of the root system could also be related to root mass; stem diameter being a commonly used allometric indicator (Paul *et al.*, 2005).

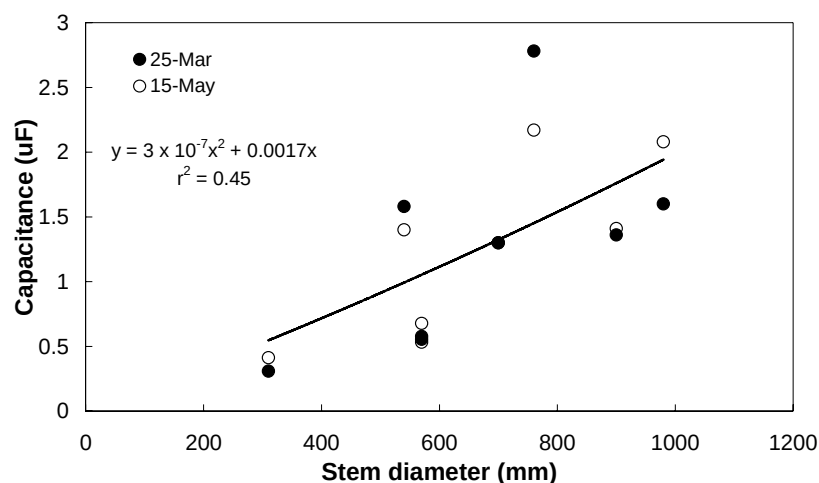


Figure 1 Preliminary capacitance C measurements undertaken on *Pinus radiata* Pialligo. The relationship between C and stem diameter suggested C may also be related to root mass, as root mass typically increases with increasing stem diameter (from Ellis *et al.*, 2008).

To investigate this further, in 2005 we undertook C measurements on a further 11 trees (*Eucalyptus cladocalyx* and *Corymbia maculata*), which were being destructively sampled at 4 locations for a complete biomass inventory, as part of another project (see Paul *et al.* 2005; Table 1).

Table 1 The four sites used for low frequency capacitance measurement in 2005. Site details and tree characteristics can be found in Paul *et al.* (2005).

Site name	Latitude and longitude (°)	Age at harvest (y)	Species
Apex Park	-36.09, 147.05	40	<i>C. maculata</i>
Laurundal	-35.65, 146.81	48	<i>E. cladocalyx</i>
Woodlands	-37.65, 144.85	ca. 80	<i>E. cladocalyx</i>
Yallock	-35.66, 147.53	13	<i>C. maculata</i>

The destructive sampling was undertaken specifically to develop allometric relationships for predicting the below ground biomass of forest trees. Roots were dug from the soil mechanically and sorted manually into 3 diameter fractions: 2 – 5 mm, 5 – 15 mm and > 15 mm. Detailed descriptions of the sites, the trees and the harvesting methods used can be found in Paul *et al.* (2005). Fine roots (<2 mm diameter) were not measured but their mass was estimated using the method of Mokany *et al.* (2006) who related fine root length to above ground biomass

$$R_{<2} = -0.05 \ln(BM_{ag} + 0.39); r^2 = 0.43, \quad [1]$$

where $R_{<2}$ is the proportion of roots < 2mm diameter and BM_{ag} ($Mg\ ha^{-1}$) is above ground biomass. However, there is considerable uncertainty associated with this relationship ($r^2 = 0.43$). Fine roots estimated in this way represented about 30% of total root mass at the younger site (Yallock) but only 1 to 16 % of total root mass at the other sites. Root length was not measured in the experiment, but for the purposes of comparing length with C , we estimated total root length from root mass and geometrical assumptions. Roots were assumed to be cylindrical and the representative diameter of each fraction was taken to be the mid point e.g. for the 2 to 5 mm fraction, the representative diameter was set to 2.5 mm. For the fine roots (<2 mm diameter), the representative diameter was set to 1 mm. A root wet density of $0.95\ g\ cm^{-3}$ for all root mass fractions was approximated from density measurements of woody and non-woody roots of other species – this study. Fine root length estimated from the above methods represented <90% of total root length for all trees, however this is not unusual, as it is widely accepted that fine roots represent the majority of root surface area (and therefore length) in most plants. We found that, although the total overall root length was very sensitive to the representative diameter of the fine root fraction, and also root wet density, the relative differences in total root length between trees and between sites was relatively insensitive to these two parameters. There was very little sensitivity to a difference in density between fine roots and coarse roots. However, the relationship showed the greatest sensitivity to the length of fine (<2 mm) roots, estimated from Equation [1] and geometric considerations.

Results

Figure 2 shows the relationships between total root mass and capacitance C at the 4 sites described briefly in Table 1. At all sites C increased with increasing root biomass. Data from three of the sites formed a relatively consistent relationship. This is both encouraging and surprising, given the differences in species and site conditions. Data from the Yallock site fell outside the general pattern, which we suspected was related to a larger proportion of fine roots (<2mm) at Yallock, being a much younger plantation (Table 1; see also below).

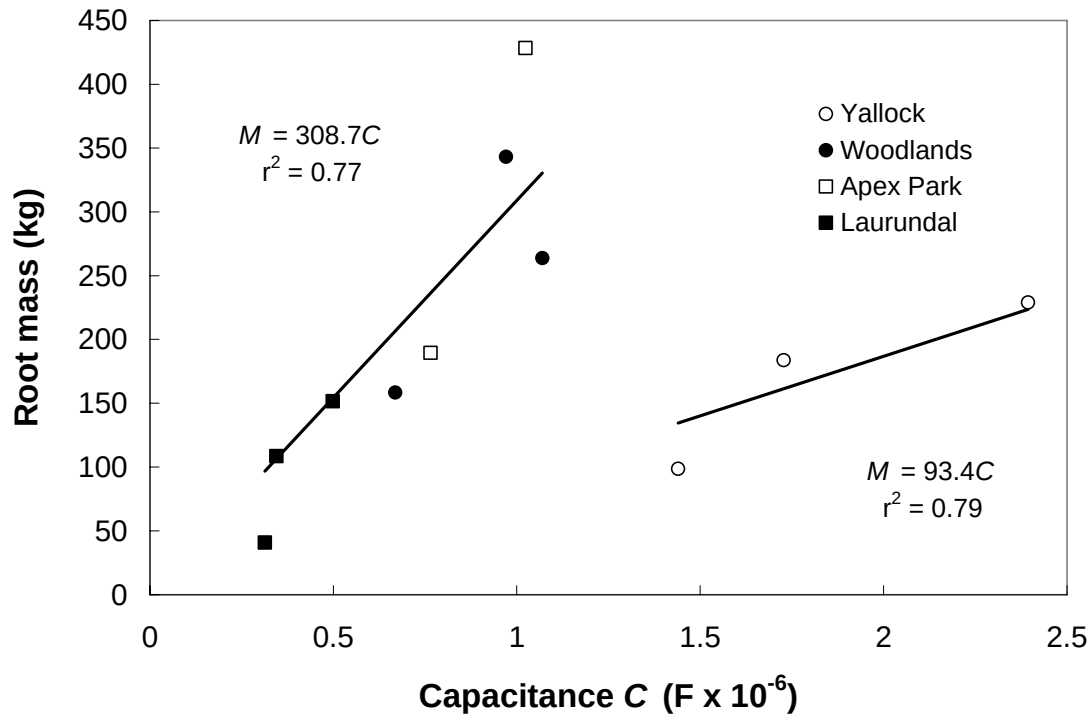


Figure 2 Relationship between capacitance C (4-terminal method) and total root mass M harvested from 11 plantation eucalypts. Fitted linear relationships are forced through the origin.

We compared C measurements using both 2 and 4 terminal methods (Ellis *et al.*, 2008). These showed that the 4-terminal method successfully removed the effects of probe contact impedance, resulting in a higher, and presumably more accurate, measurement of root system capacitance C . We found similar relationships between C and the coarse root mass fractions, but a stronger general relationship between C and the mass of fine roots alone. This is consistent with the theory of Dalton (1995), which proposes roots to be cylindrical capacitors and therefore C is more strongly related to total root length than root mass.

Figure 3 shows the relationship between capacitance C and root length, inferred from root mass and geometrical assumptions. Compared to Figure 2, root length data from all sites (Figure 3) appear to form a single relationship. Due to the larger proportion of fine roots, the Yallock site had a much greater estimated total root length, and a strong, positive gradient with C . Of the other 3 older sites, root length at Laurundal also displayed a positive gradient with C but the remaining two sites showed no gradient, or a very slight negative gradient, for which we have no explanation at this stage. Although total length was sensitive to assumed root wet density and the representative diameter of the fine root fraction, the distribution of data points was relatively insensitive to these two parameters and they did not significantly affect the precision of the relationship shown in Figure 3. Because fine roots (<2mm) represented <90% of root total root length, omission of the coarse root fractions did not significantly alter the relationship. The uncertainty of Equation [1] represented the largest possible source of error and we investigated the sensitivity of our findings to this. A 100% variation in root mass (and therefore the length) of fine roots from the Yallock site significantly altered the precision and slope of the fitted relationship in Figure 3. However, due mainly to the ‘leverage’ of the Yallock data points, a strong relationship between C and root length remained, even when the inferred diameter of the ‘fine’ roots was altered between sites.

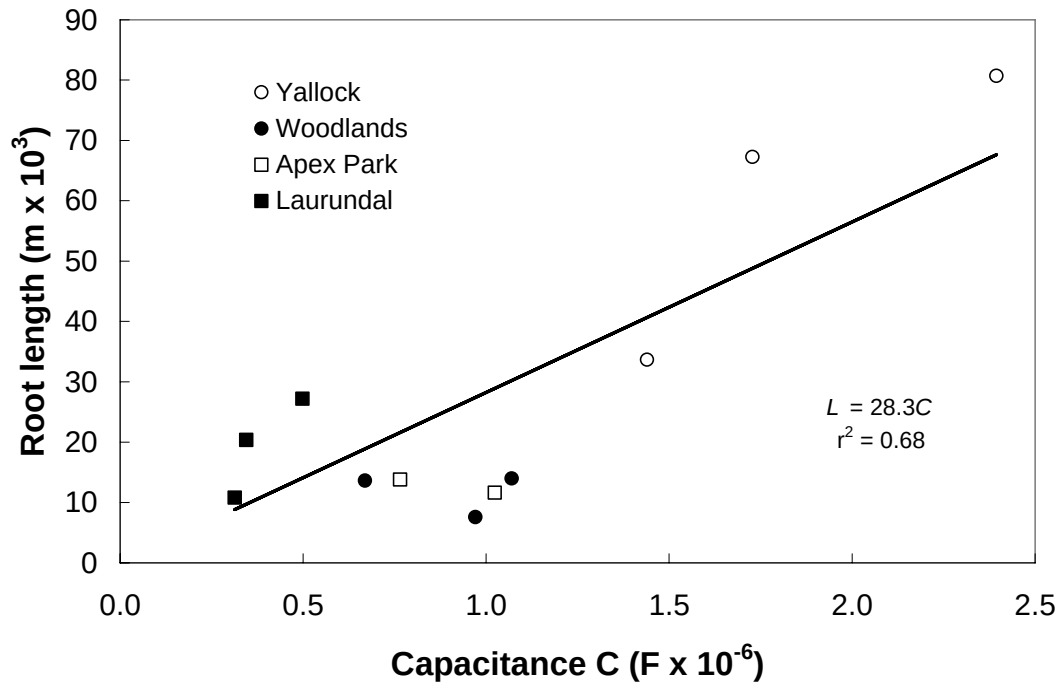


Figure 3 Capacitance C versus root length L , estimated from root mass (Mokany *et al.*, 2006), diameter fractions and root mass densities. The fitted linear relationship is forced through the origin.

Discussion

Our results have demonstrated positive relationships between capacitance C and root mass for 11 trees spread over 4 different sites. The relationships for three sites appeared similar, with the Yallock site having greater C (by about half an order of magnitude) for the same root mass. Trees at the Yallock site were *C. maculata*, but this species was also represented at the Hume site, which showed a similar relationship to those at the *E. cladocalyx* sites (Greenvale and Laurundel), so there is little evidence that this was due to species differences.

However, when capacitance C was plotted against root length (inferred from geometric and allometric relationships) a more general relationship was fitted across the four sites. Figure 3 suggests that the greater proportion of fine roots at (the younger) Yallock may be the main reason for a different C – root mass relationship at that site. This is consistent with the Dalton (1995) root capacitance theory. Dalton (1995) likened roots to cylindrical capacitors and therefore C will be proportional to total root length (for roots of the same diameter). Given that the three mature sites, together, formed a relatively coherent relationship between C and root mass (Figure 2), this suggests a relatively constant relationship between total root mass and root length. This is consistent with the notion that growth rates at the older sites had stabilised, as is typically observed in plantations, but trees at the younger site (Yallock) was continuing to explore their potential root zone and had a larger proportion of fine roots. However, we emphasise that fine roots were not measured in this experiment and the relationship between C and root length is, at best indicative.

The potential errors associated with the estimation of fine root mass via the method of Mokany *et al.* (2006) should be noted ($r^2 = 0.43$). However, our sensitivity analysis showed that a potential 100% error in the estimation of root at the Yallock site weakened, but did not disqualify a strong relationship between C and root length. In our estimation of root length, from root mass and geometric considerations, we introduced further uncertainty, which could have resulted in significant error in absolute root length. However, our sensitivity analysis also showed that this did not significantly affect the precision of the relationship between capacitance and total root length.

It appears, therefore, that the fine root (<2 mm) fraction could be greatest determinant of capacitance C , and is consistent with capacitance-root theory (Dalton, 1995). It is therefore likely that the relationships between C and root mass were likely due to an allometric relationship between root mass and the proportion of fine roots. Such an allometric relationship is likely to depend on the above ground biomass, and possibly the age of the trees.

Conclusions

We believe this is the first published evidence of a relationship between C and root mass and root length of plantation trees. This experiment, although having limited data, showed conclusively that the electrical capacitance C was related to the root mass of *Eucalyptus cladocalyx* and *Corymbia maculata* at the four sites investigated. At each of the sites, C consistently increased with increasing root mass and data from three of the sites formed, more or less, the same relationship. Data from the remaining (Yallock) site showed about 4 times the gradient and about half the capacitance for similar root masses. We attribute this difference to the greater proportion of fine (young; <2 mm) roots at the Yallock site. It is likely that this was due to the relative youth (14 years, compared with 40, 48 and ca 80 years) of the Yallock site. Although there were potentially significant errors in the estimation of the mass and length of fine roots, they appeared to be the main determinant of the capacitance of the root system. Capacitance was also clearly dependant on total root mass, however we suggest that this is likely due to allometric relationships between total root mass and the proportion of fine roots. This, in turn, could depend on above ground biomass, but is more likely to depend on tree age.

High frequency location of roots

Introduction

Any conductor transmitting an alternating current will have associated with it oscillating electric ‘E’ field and magnetic ‘H’ field. The strength of these fields will vary with distance from the conductor, and will oscillate at the same frequency as the alternating current. In a previous JVAP study (Ellis *et al.*, 2008), we hypothesised that high frequency (in the MHz range) excitation of a plant would propagate electric signals (currents) in the root system. Preliminary investigations at 1 MHz provided evidence that this was the case and that the electric fields associated with the currents could be detected remotely, at least on tree roots 10 to 25 mm in diameter, using tuned dipole antenna probes (Figure 4).

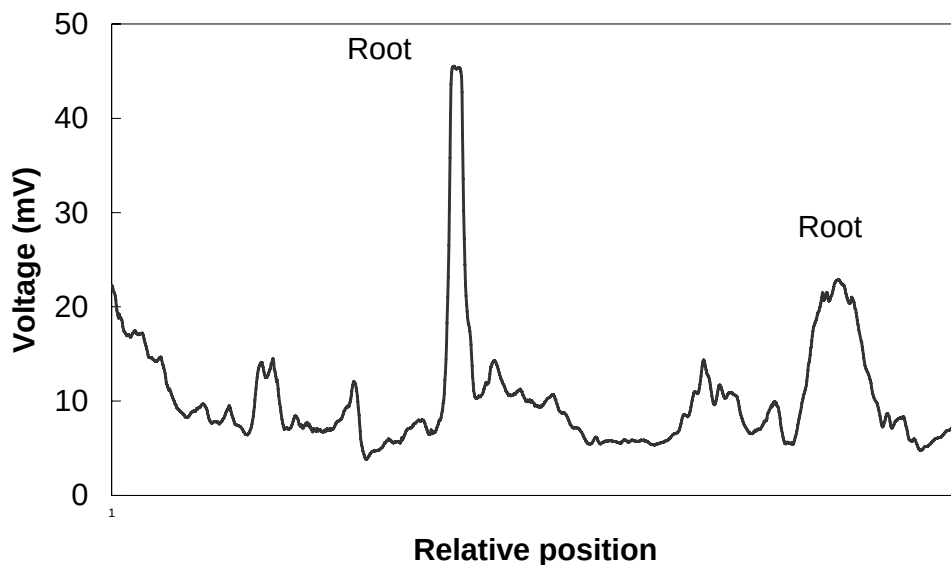


Figure 4 Voltage signal indicating electric field strength associated with two shallow, lateral tree (Brush Box; *Lophostemon confertus*) roots. Relative position of the measurements is indicative only; the total distance from left to right represents a horizontal sweep of approximately 1 m at right angles to horizontal roots (from Ellis *et al.*, 2008).

Subsequently, we sought a frequency which would be most efficient for the transmission of signals in roots. Impedance (Z_r) is the property of a material to resist the flow of an alternating current and often varies with frequency. The lower the impedance of a root, the greater the opportunity for signal propagation. In the laboratory, we measured Z_r of a number of herbaceous and woody root specimens and found that Z_r was quite substantial at low frequencies but relatively low (1 to 2 k Ω) at frequencies between 10 and 20 MHz (Figure 5). In addition, for the root samples tested, Z_r remained relatively constant with length after about 60 mm. Although this was only a preliminary test, it suggested that roots might be able to transmit signals throughout the root system at high frequencies (10 to 20 MHz).

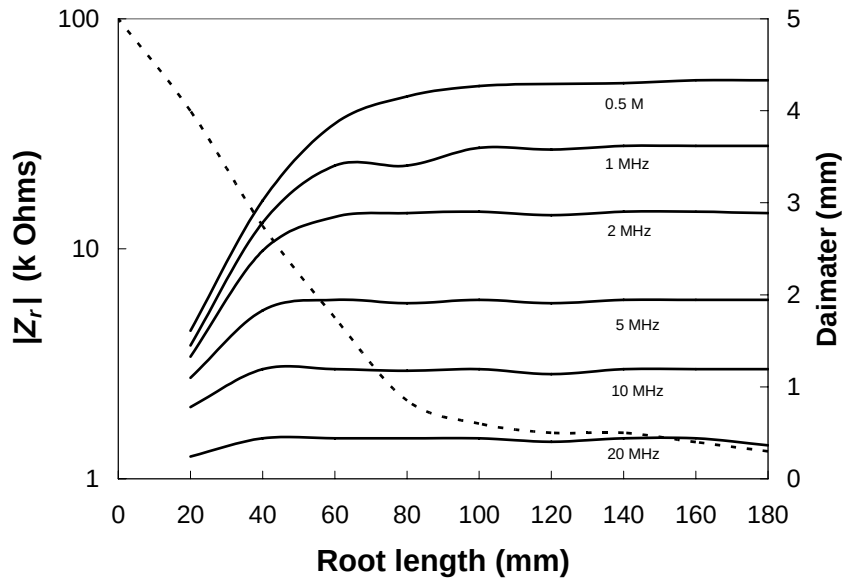


Figure 5 Measured impedance magnitude $|Z_r|$ of an isolated bean root (*Vicia faba*) as a function of frequency (log scale), root length and root diameter (dashed line).

A portable instrument (vector volt meter plus source; see Appendix; Figure 15 to Figure 19) was therefore constructed to allow simultaneous excitation of plants at 16 MHz and the detection of electric E (or magnetic H) fields associated with roots. Figure 6 illustrates the increase in field strength with proximity to lateral roots of a small acacia tree when excited at this frequency. This supported our earlier suspicions that, when a tree stem was electrically excited, signals propagated throughout the root system, although the exact mechanism for this behaviour was not understood. We therefore proposed an hypothesis that roots may act as ‘antennas’, or leaky transmission lines, within a soil medium and we undertook some laboratory experiments to test this.

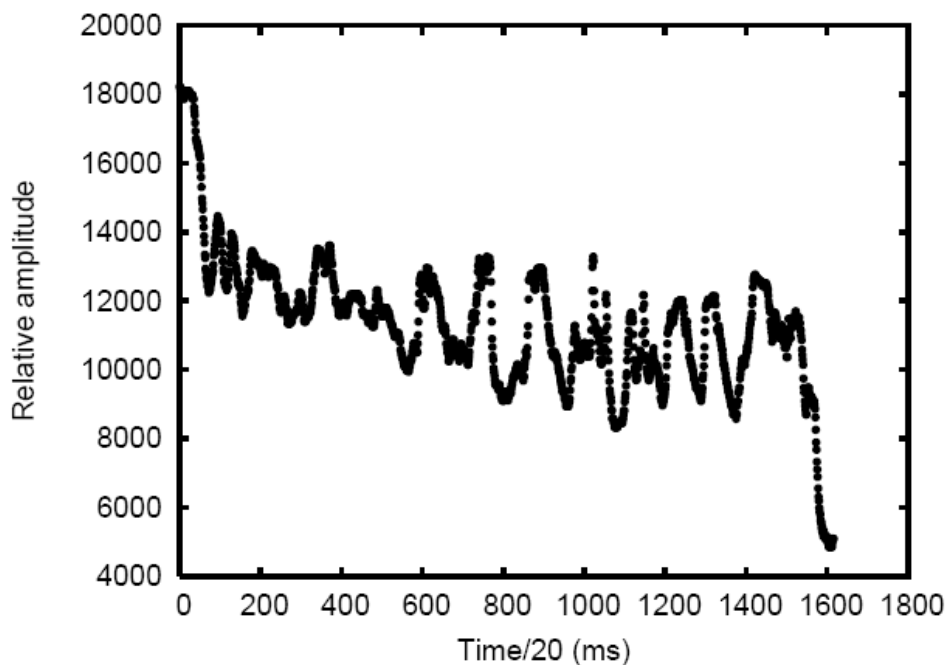


Figure 6 The relative amplitude of the magnetic field signal detected from a 10 to 20 mm diameter lateral root of an acacia tree (*Acacia* sp.), measured 50 times each second. The tree stem was excited at 16 MHz using an induction loop. Peaks and troughs indicate changes in field strength as the detector probe was swept backwards and forwards across the root.

The next section describes the relevant electromagnetic theory of antennas embedded in a soil medium and the two laboratory experiments: 1) attenuation (i.e. signal loss) experiment; and 2) measurement of root and sand dielectric properties.

Methods

The detection of signals from tree roots (Figure 6) suggested that the excitation of the tree propagated a signal in the root system, but the actual current path was not known. A linear antenna embedded in a soil medium can either transmit signals along its length, or signals can ‘leak out’ into the surrounding soil, depending on the relative electromagnetic properties of the soil and the antenna. King and Smith (Ch 7; 1981) describe these conditions for both an insulated antenna and a transmission line, much like a coaxial cable. Figure 7 shows the simpler case - a root, idealised as an antenna, embedded in soil. Here we assume the root core to be a highly conducting material and the epidermis to be a dielectric (i.e. it has both conducting and capacitive properties).

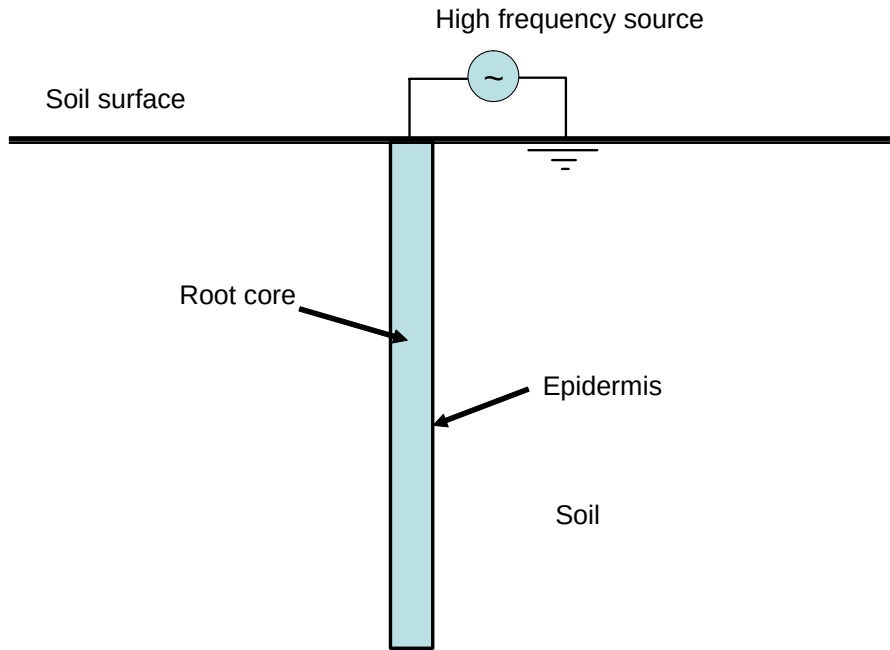


Figure 7 A conceptual model of an idealised cylindrical root in cross-section, embedded in a soil medium and excited by a high frequency source. The root core is assumed to be highly conducting and the epidermis to be a relatively dense dielectric.

King and Smith (Ch 7; 1981) describe the behaviour expected of such an antenna, depending on the relative dielectric density of the epidermis and the soil. Dielectric density is related to what is called the ‘wave number’ $\bar{k}$

$$\bar{k} = \omega(\mu\bar{\epsilon})^{1/2}, \quad [2]$$

where $\bar{k}$ is the wave number, ω is frequency, μ is the permeability of free space, $4\pi \times 10^{-6}$ Wb/A/m and $\bar{\epsilon}$ is the permittivity of the material. Both wave number and permittivity are complex values i.e. they have real and imaginary components which relate to the conductive and capacitive behaviours, respectively. If $\bar{k}^2$ of the epidermis has a greater magnitude than the soil, then electromagnetic waves in the root core will be totally internally reflected (and also travel along the surface of the epidermis) and therefore will be transmitted along the root. That is, the inequality:

$$|\bar{k}^2_{epidermis}| \gg |\bar{k}^2_{soil}|, \quad [3]$$

where the vertical bars indicate the absolute value of the complex $\bar{k}$. Alternatively, if the converse is true, electromagnetic waves ‘leak out’, with significant power loss, into the surrounding soil. King and Smith (Ch 7; 1981) also describe the more complicated case of a transmission line, comprising

multiple layers of dielectric but, structurally, it is too complicated for our knowledge regarding root internal structures and current paths.

To test the antenna model of a root in soil we measured the attenuation of a signal after it was passed through a 300 mm length of root embedded in sand. Three agapanthus (*Agapanthus africanus*) roots were chosen because of their relatively constant diameter (5 to 7 mm) and lack of branching. The roots, which were flexible, ‘fleshy’ and non-woody, were dug from a local garden and transported to the laboratory in plastic bags. They were cleaned by brushing and placed along the centreline of 90 mm diameter PVC pipe filled with sand (see Appendix; Figure 21). Electrical connection to a network analyser (Advantest R3961B; see Appendix; Figure 21) was made at each end of the root via 0.25 mm diameter, 5 mm long wire probe inserted axially into the root. Tests were undertaken using dry sand (0.44% v/v volumetric water content) and wet sand (33.8% v/v), wet up in a bucket and mixed thoroughly by hand. A third water content (24.1% v/v) was used by allowing the wet sample to dry in air overnight. Following the experiment, root diameters were measured using callipers. Water contents, wet and dry bulk densities were determined following weighing and drying at 40° C for several days, until there was no change in mass. Sand volumetric water content was determined from a sub sample after each test; dry bulk density (1.3 g cm⁻³) was determined from the same samples; and particle size distribution was determined by dry sieving (see Appendix; Figure 22).

Signal attenuation X_{db} was recorded in decibels (db) between 300 kHz and 3.6 G Hz.

$$X_{db} = 20 \log_{10} \frac{X}{X_0}, \quad [4]$$

where X_0 and X are the input and output signal strengths, respectively.

To help interpret the results of the attenuation experiment, we measured the permittivities of root material (3 replicate samples) and sand (one sample) at frequencies between 10 MHz and 1 G Hz using a Hewlett Packard 85070B dielectric probe, connected to a Hewlett Packard 8714ES network analyser (see Appendix; Figure 23). For comparison with sand, the permittivity of a single sample of saturated loam was also determined as a ball-park value for a ‘real’ soil. The permittivities were used to calculate wave numbers for the sand, loam, the root core and root epidermis materials (Inequality [3]). To obtain samples of appropriate dimensions for testing with the dielectric probe, agapanthus root core was mashed using a mortar and pestle and placed in a container so that the sample was about 10 mm deep. Root epidermis was carefully removed using a blade, scraped with a blunt edge and then allowed to dry in air for a few hours to remove liquids from ruptured cells. This process resulted in a sample 1 to 2 mm thick, with the epidermis on one side. Multiple samples were measured in a stack to provide adequate sample thickness of 5 to 10 mm. For comparison with the fleshy agapanthus root, a woody hakea (*Hakea sp.*) root (~25 mm diameter) was also sampled from a local garden. Permittivity, moisture content and density measurements were made on the inner (woody) material of the root and the root bark.

Results

The presence of an agapanthus root significantly improved signal transmission through the sand, however, generally, the attenuation, and therefore the loss of signal, was very high. Figure 8 shows the attenuation (db/m) of the signal passed through wet and dry sand, and the agapanthus roots embedded in sand, between 300 kHz and 1 GHz.

Between 300 kHz and about 30 MHz, the signal through dry and wet sand, respectively, was reduced by about -325 and -275 db/m. This is a very large loss given that an attenuation of -100 db/m means that the output signal will be 1×10^{-5} (five orders of magnitude smaller) of the input signal, after travelling a distance of 1 m (Equation [4]). However, given these significant losses, it is clear that the presence of the root significantly improved signal transmission by about 200 db/m and 125 db/m in dry sand and wet sand, respectively. This represents up to ten orders of magnitude increase in signal strength, compared to sand alone. It is also clear from Figure 8 that wet sand improved signal transmission in the root, compared to dry sand, between 10 MHz and 100 MHz. This is consistent with the antenna theory, which indicates that the signal is likely to be ‘more confined’ by a denser dielectric (i.e. wet sand vs dry sand). This is supported later by dielectric measurements of the individual materials. However, there was very little difference in the effects of dry or wet sand, on root signal transmission, between 300 KHz and 10 MHz.

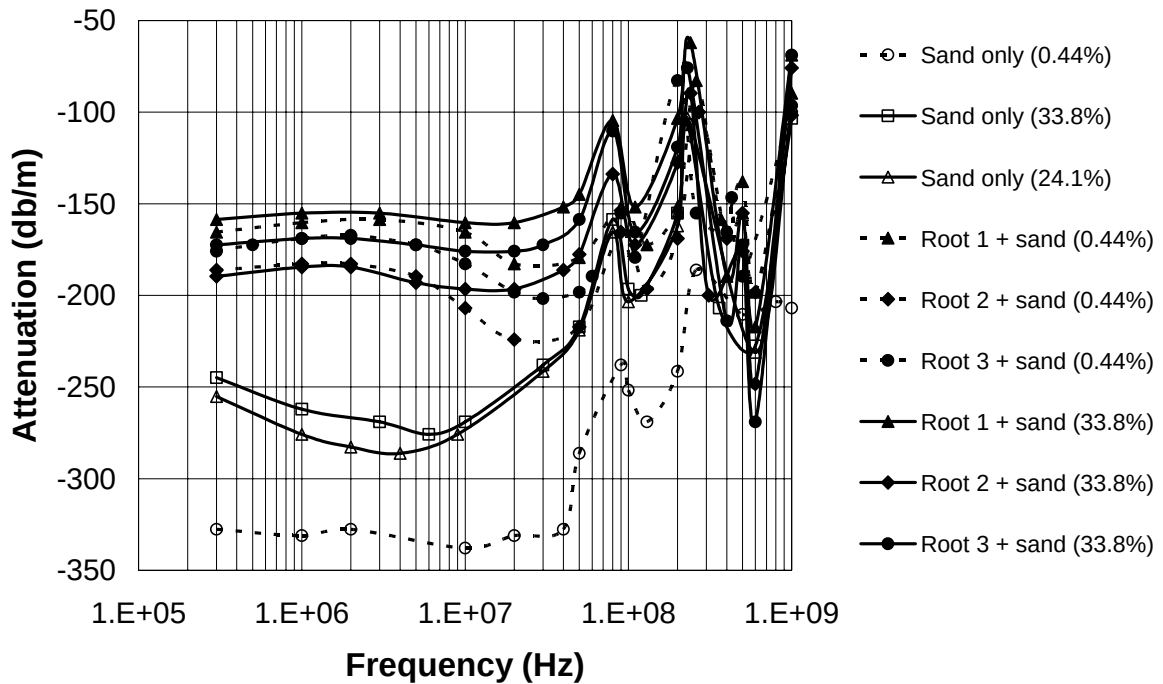


Figure 8 Attenuation (db/m), or loss of signal passed through three agapanthus (*Agapanthus africanus*) roots embedded in dry sand (0.44 %v/v) and wet sand (33.8% v/v). Overall, signal loss was very high. Wet sand, by itself transmitted a stronger signal (i.e. less negative attenuation) than dry sand, and the roots improved signal strength in both dry and wet sand. The wet sand improved signal strength relative to dry sand above about 10 MHz. Volumetric water contents of all materials are shown as percentages.

There was a consistent increase in signal transmission with increase in root diameter (Figure 9) between 5 and 6.75 mm. Although this was not a large diameter range, and it is difficult to extrapolate from such a parsimonious data set, it appears safe to assume that smaller diameter roots will have higher transmission losses and *vice versa*.

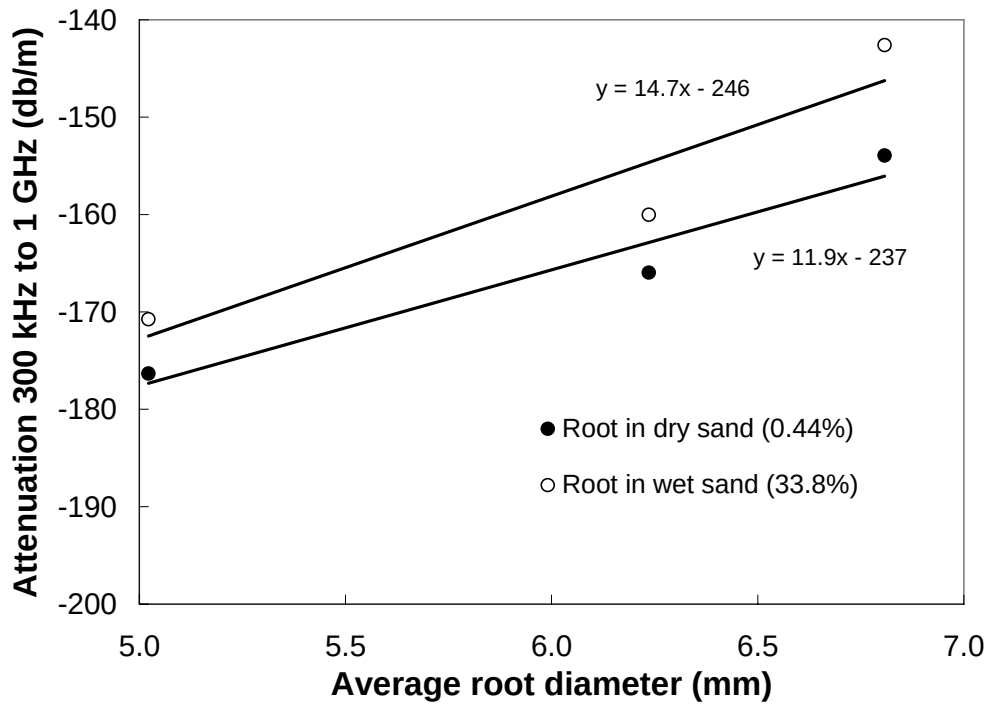


Figure 9 Signal attenuation (db/m) over the frequency range 300 kHz to 1 GHz relative to average diameter of the three agapanthus roots in wet and dry sand.

Relative permittivity E_a (i.e. the permittivity relative to that of a vacuum) values for sand and root materials, between 10 MHz and 1 GHz, are shown in Figure 10. Here we show E_a as the absolute value of the complex (i.e. having a 'real' and 'imaginary' components) permittivity $\bar{\epsilon}$. For all the materials tested, E_a generally decreased with increasing frequency, although wet sand showed a relatively constant value. The dry (0.44 % v/v) sand showed the lowest values by at least one order of magnitude, compared to the other materials. The saturated loam showed a much higher permittivity than the wet sand but was comparable to the (high water content) agapanthus roots. Overall, there was an increasing trend in E_a with increasing moisture content.

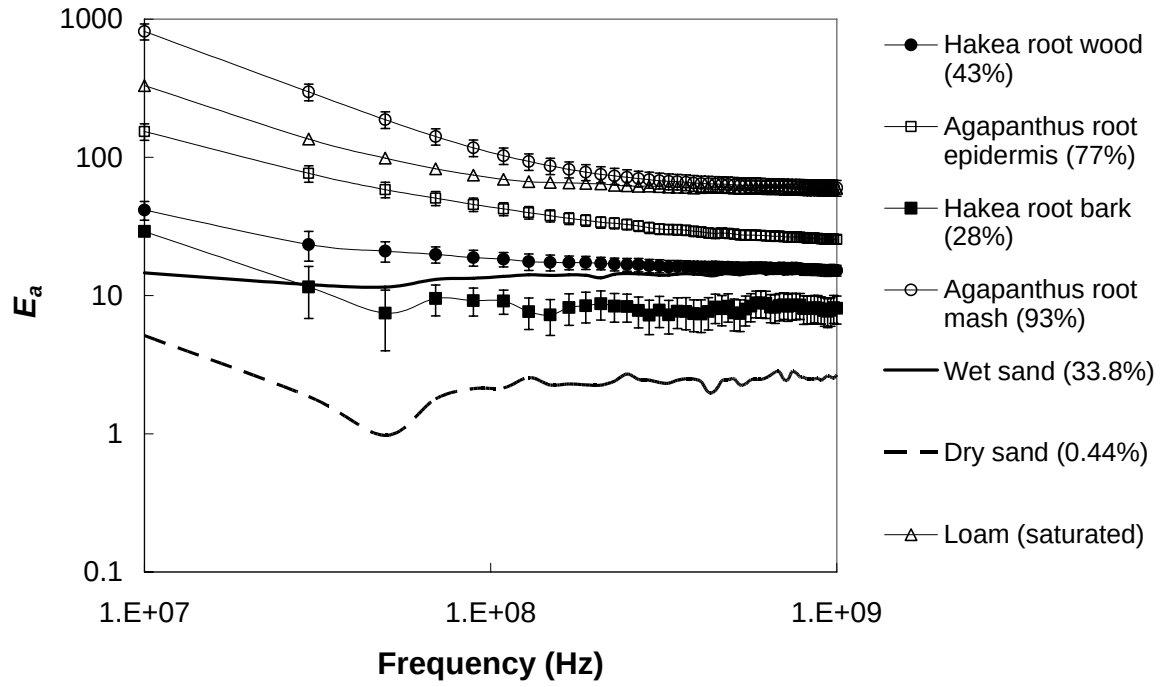


Figure 10 Relative permittivity of the agapanthus (*Agapanthus africanus*) root materials and sand used in the attenuation experiment (Figure 11). For comparison, the wood and bark of hakea (*Hakea sp.*) root and saturated loam were also tested. Percentages indicate moisture content of all materials.

E_a was used to calculate wave numbers $\bar{k}$ for sand and the root materials, which are shown in Figure 13. The conditions for signal transmission (Inequality [3]) $|\bar{k}_{epidermis}^2| \gg |\bar{k}_{soil}^2|$, appear to be satisfied (Figure 10), by about two orders of magnitude at frequencies in the MHz range. That is, the epidermis was much more dielectrically dense than the surrounding medium (sand), and therefore total internal reflection of the signal should occur i.e. the agapanthus root should transmit a signal efficiently (Ch 7; King and Smith, 1981). However, the attenuation experiment (Figure 8) did not show this at all, and it is likely much of the signal ‘leaked out’ into the surrounding sand. The most likely reason for this is that the root core (agapanthus root mash; Figure 13) was more dielectrically dense than either the sand or the root epidermis. That is, the gradient of dielectric density indicated by the magnitude of the wave numbers from the root centre, to the epidermis to the surrounding material is in the opposite direction for total internal reflection to occur. If the saturated loam was considered as the medium surrounding the root, although it showed a substantially higher wave number than the sand, it is still unlikely to provide improve the conditions for signal propagation along the root.

Although we did not measure signal attenuation in a hakea root specimen, Figure 12 shows that the dielectric density gradient root wood > root bark > sand would determine that much of the signal would also be likely to ‘leak out’ and not be transmitted.

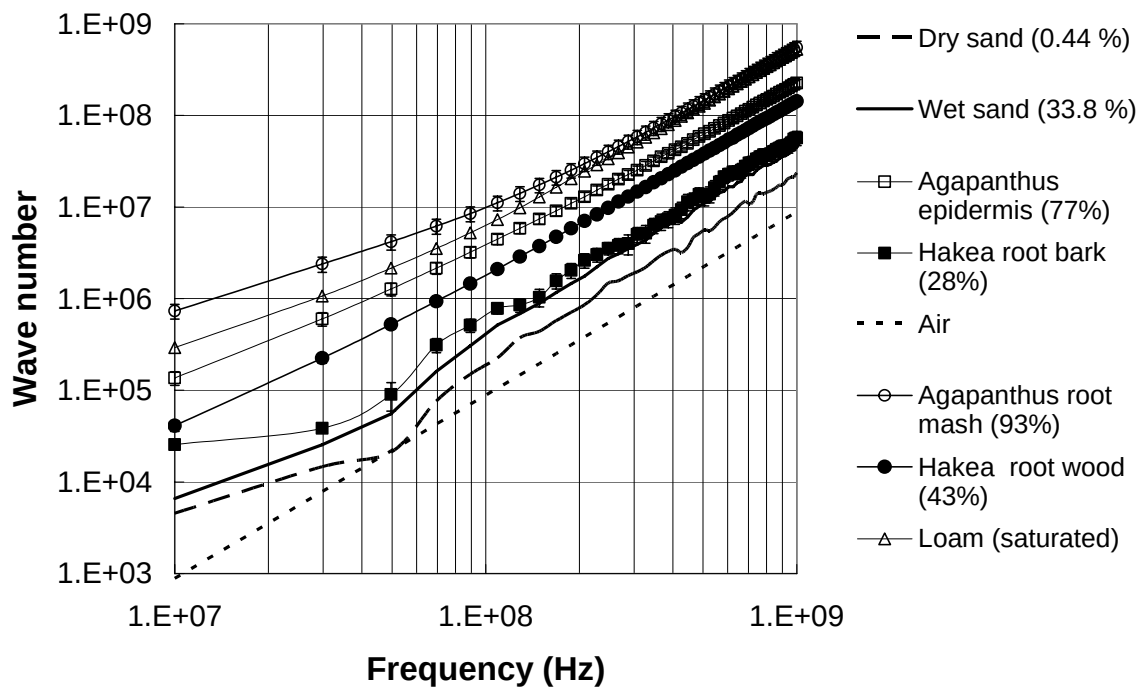


Figure 13 Wave numbers are a measure of the dielectric density of a material (Inequality [2]) and are shown here for the root and sand materials used in the attenuation experiment (Figure 14). For comparison, the wave numbers of air and the woody and bark portions of hakea root and saturated loam are also shown. Moisture contents (v/v) are shown as percentages.

Discussion and conclusion

Initial tests on tree roots in the field (Figure 4; Figure 6) showed that, when a tree was excited (in the MHz range) a signal, which was transmitted from the stem to the roots, could be detected via the associated electric or magnetic field. These fields were detected in exposed and buried (50 – 100 mm deep) roots. This stimulated interest in the possible development of an electrical method for the location of plant roots in soil. However, our hypothesis that the dielectric properties of tree root and soil materials were conducive to the transmission of high frequency signals in soil, much like an antenna, appears to be false. That is, under laboratory conditions, signal attenuation was very high (Figure 8), indicating that, rather than travelling longitudinally along the roots, the signals ‘leaked out’ into the sand. Further, not all of the conditions were present for a root to act as an antenna or transmission line. That is, although the dielectric density (as indicated by wave number; Inequality [3]) of the root epidermis was greater than the dielectric density of the soil, the root core material could not be considered to be good conductor. In fact, the dielectric density of the root core material was greater than either the epidermis or the soil. This created a dielectric density gradient in the opposite direction required for the conceptual model of the antenna to be valid.

Our attenuation measurements were undertaken with sand, however, we do not expect substantial differences if roots were embedded in real soil. The dielectric properties of the saturated loam were unlikely to enhance signal transmission along a root. Similarly, the dielectric properties of a further six soils from the USA, including loams, clays and silty soils give no cause to expect this to be markedly different for any agricultural or forest soils (Logsdon, 2005). It also appears that it is unlikely that the root dielectric properties of other species would be more conducive to signal transmission as indicated by woody hakea root and root bark (Figure 13). In addition, the dielectric density of the root materials increased with moisture content and, at least the young roots of pea (*Pisum sativum*), barley (*Hordeum vulgare*), willow (*Salix sp.*) and maize (*Zea mays*) grown in a laboratory all had moisture contents between 91 and 96 % v/v (Glyn Bengough, Scottish Crop Research Institute, Dundee; unpublished data). We would expect that these roots would have similar dielectric properties to the agapanthus roots we tested in this study.

King and Smith (Ch 7; 1981) also present the theory and conditions for signal transmission in a transmission line, similar to a coaxial cable, embedded in soil. The transmission line model described comprised a highly conductive cylinder, filled with, and surrounded by, an insulating material. This structure is encased within a second sheath of insulating material and the whole structure is surrounded by soil. Simply put, conditions for signal transmission in this case require that $\left| \bar{k}_{soil}^2 \right| \gg \left| \bar{k}_{epidermis}^2 \right|$ and $\left| \bar{k}_{soil}^2 \right| \gg \left| \bar{k}_{root\ core}^2 \right|$, but our measurements show that neither of these conditions were likely to be met by either agapanthus or hakea roots. It appears, therefore, that while the tree roots tested in the field (Figure 4; Figure 6) were verified as transmitting a signal following excitation of the tree stem, signal losses (attenuation) along the length of the root would have been very high. This is consistent with the signal being undetectable after 2 to 3 m from the tree stem during the field tests.

Although we did not measure a large range of root diameters, Figure 9 shows that signal loss will increase rapidly with decrease in root diameter, and it is highly unlikely that small diameter roots (1 to 2 mm) would transmit a useful signal.

Implications and Recommendations

These results are relevant to researchers of plant root systems and we have identified some theoretical and practical limits of electrical measurement. In this preliminary project, however, we were unable to develop the methods to a point that they are likely to be directly useful to the agricultural and forest industries.

Our recommendations relate to root research and geophysical research:

1. Since the destructive measurement of tree roots is typically a laborious and expensive process, electrical capacitance measurements should be routinely considered for preliminary investigations as they are rapid, easily performed and could augment other sampling methods. Interpretation of results should include consideration of differences in age of the trees, and hence differences in the proportion of fine roots and total root length;
2. Our preliminary results suggest the high frequency method is unlikely to provide a ready path toward the development of routine methods for the location of roots in soil. However, because our investigations were not exhaustive, we suggest that root researchers and geophysicists keep in mind the possibility that a greater efficacy in this technique may be realised through further investigation in the future.

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Appendix – Electrical equipment

Portable vector voltmeter plus source

A new vector voltmeter plus source was developed to allow the excitation of plants at 16 MHz and the simultaneous detection of electric and magnetic fields associated with roots (Figure 15). Specifications for the instrument are given in Table 2 and sketches of three possible methods of connection to a tree are shown in Figure 17.



Figure 15 Portable vector voltmeter plus source developed to allow simultaneous excitation of plants in the field. This was used in conjunction with tuned receiver probes to detect electric and magnetic fields associate with plant roots.

Table 2 Specifications and settings for the portable vector voltmeter (Figure 15).

Specifications:

Maximum number of files: 80
Total internal memory capacity: ~3hours (16 bit)
Flash
Download format: ASCII (test)
Battery: 12V, 2 Ah SLA
Frequency range: 62.5 kHz to 16 MHz
Data sample rate: 50 samples/sec
Maximum operating current: 130 mA
Display: 20 by 2 character LCD
Phase: -180° to $+180^{\circ}$
Amplitude: 0 to approximately 46,340 (depending on offsets)
Low battery cut-out: 10.5 V
Auto calibrate at power-on

Settings required for download

Baud:19200
Data bits: 8
Parity: None
Stop bits: 1
Flow control: None

Driver

Install FTDI chip driver for USB virtual com port (vcp) when connecting to pc for the first time.
Drivers R9052151.zip or P8002104.zip (XP certified)

Electric and magnetic field detection probes

Three types of tuned receiver probes were developed for the detection of fields associated with plants during high frequency (16 MHz) tests: 1) shielded loop magnetic (H) field sweep (or 'mop'; Figure 16; left); shielded magnetic (H) field probe (Figure 16; right); electric field E-probe. The two magnetic field H-probes were similar in appearance, designed to measure the axial and transverse components of magnetic (H) fields associated with electrically excited roots. Circuit sketches for these probes are shown in Figure 18 and Figure 19.



Figure 16 Shielded loop magnetic field sweep (left) in use with the portable vector voltmeter. Excitation of the tree is achieved using either a metal probe or, in this case, an induction loop around the stem. The electric field probe is shown on the right, connected to the vector voltmeter.

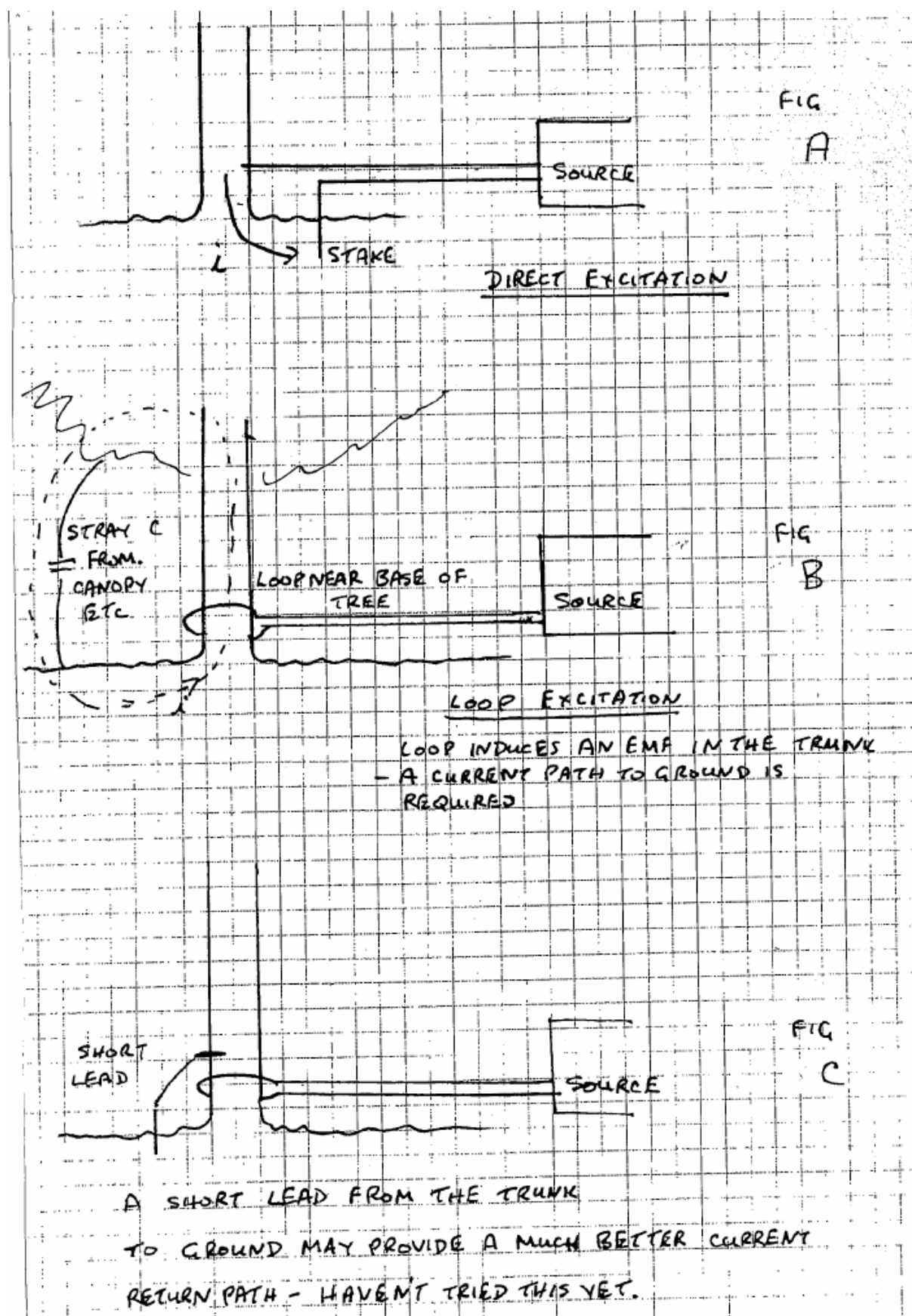


Figure 17 Three connection methods for excitation of a tree to allow detection of electric E and magnetic H fields associated with roots. E and H probes are not shown.

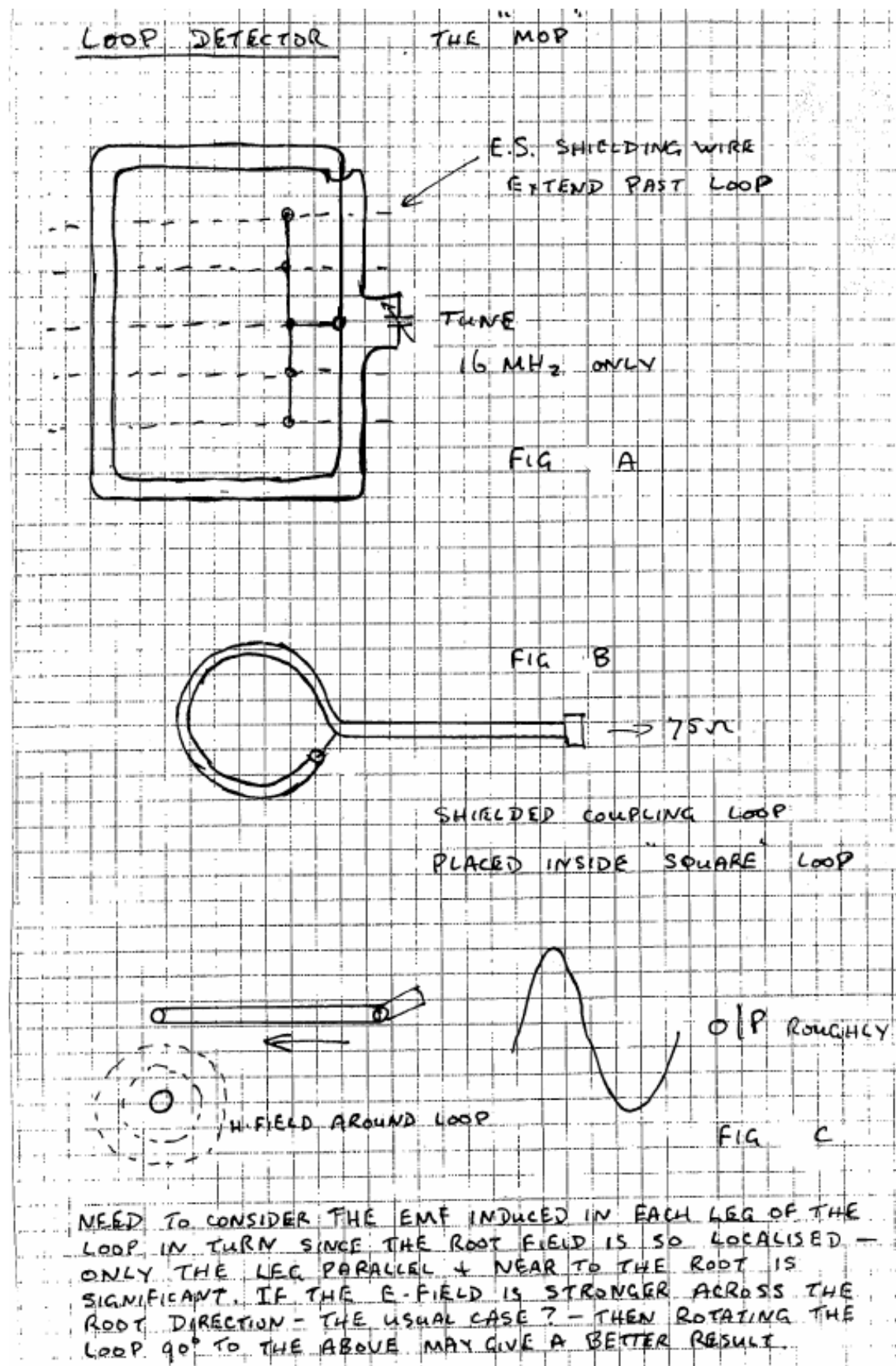


Figure 18 Circuit sketch of magnetic (H) field sweep (or 'mop') used for detecting H-fields associated with shallow tree roots.

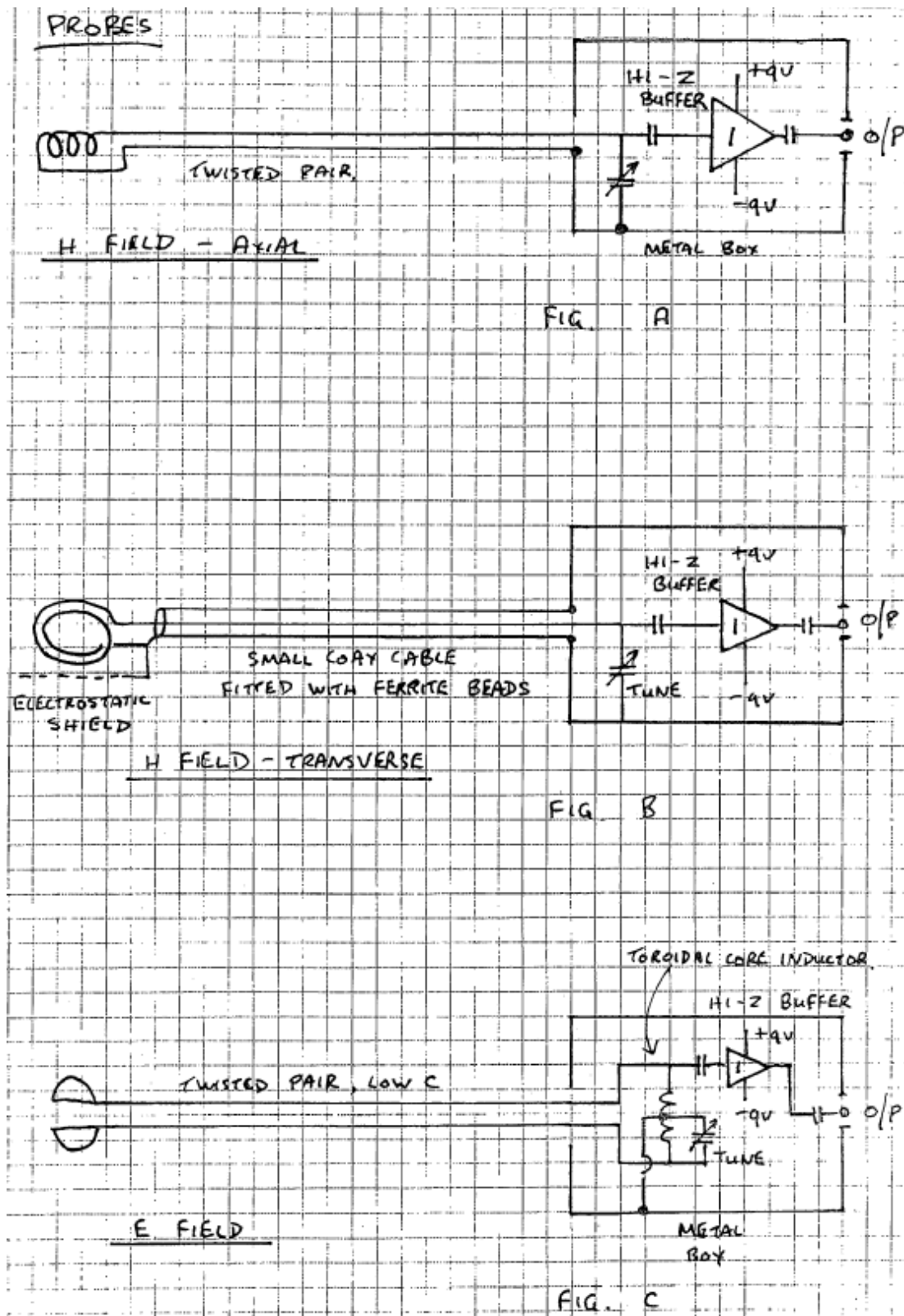


Figure 19 Circuit sketches for magnetic field probes designed to measure the axial and transverse components of the H-fields associated with tree roots, and a dipole electric field probe designed to measure the transverse E fields. An axial E probe was also built but is not shown here.

AMPS - PHANTOM POWERED

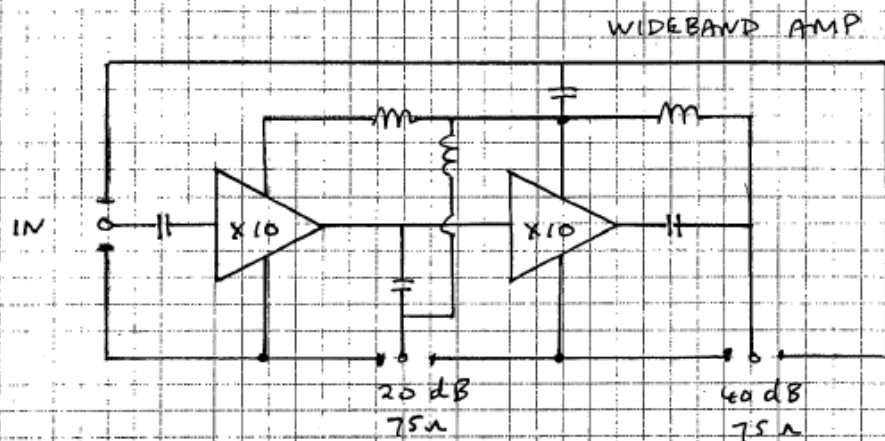


FIG A

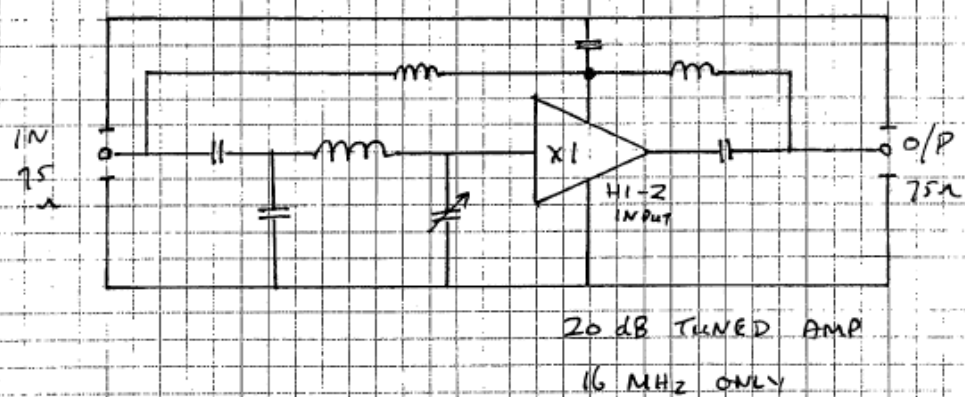


FIG B

Figure 20 Circuit sketches for the amplifiers used in series between the field detection probes and the vector voltmeter.

Attenuation experiment

The attenuation experiment measured signal loss through a 300 mm length of root embedded in sand at the centre of a 90 mm diameter PVC pipe (Figure 21). An Adventest R3961B network analyser produced the input signal and recorded the output signal.

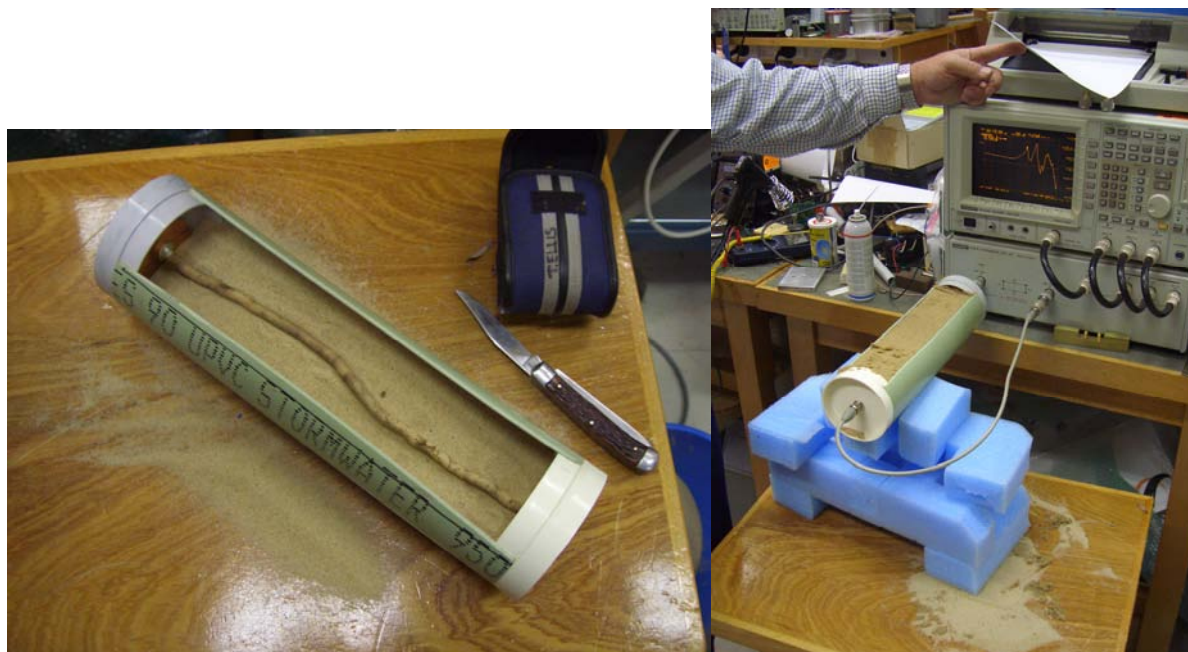


Figure 21 Experimental set up used in the attenuation experiment. A 300 mm long section of agapanthus (*Agapanthus africanus*) root is shown in the PVC pipe prior to filling with sand (left) and attached to the network analyser during testing (right).

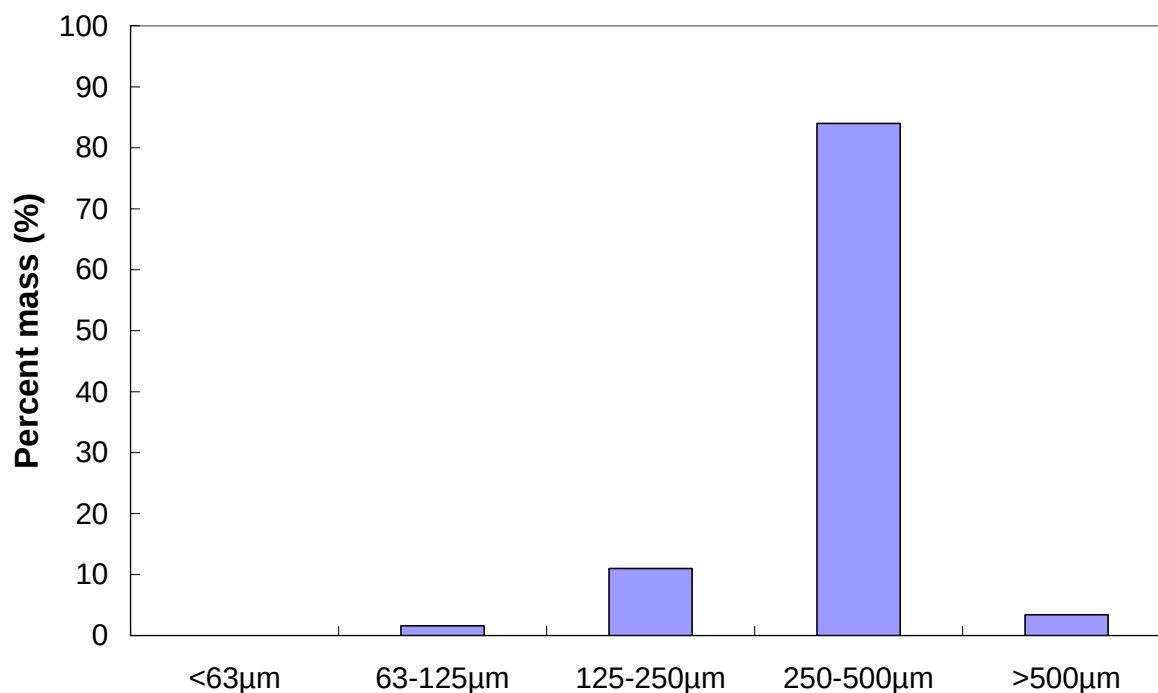


Figure 22 Particle size distribution of the sand used in the attenuation experiment.

Permittivity measurement

The permittivity of root materials and sand was measured using a Hewlett Packard 85070B dielectric probe, connected to a Hewlett Packard 8714ES network analyser (Figure 23) to help interpret the results of the attenuation experiment.



Figure 23 *Agapanthus* (*Agapanthus africanus*) root and root epidermis specimens in a Petri dish prepared for permittivity measurement (left) and the Hewlett Packard 85070B dielectric probe, connected to a Hewlett Packard 8714ES network analyser (right), measuring the permittivity of hakea root (*Hakea sp.*).