

# Prediction of Water Content of Eucalyptus Leaves Using 2.4 GHz Radio Wave

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## Abstract

Assessing plant water status is important for monitoring plant physiology. Previous studies showed that radio waves are attenuated when passing through vegetation such as trees. The degree of radio frequency (RF) loss has previously been measured for various tree types but the relationship between water content and RF loss has not been quantified. In this study, the amount of water inside leaves was expressed as an effective water path (EWP), the thickness of a hypothetical sheet of 100% water with the same mass. A 2.4331 GHz radio wave was transmitted through a wooden frame covered on both sides with 5 mm clear acrylic sheets and filled with *Eucalyptus laevopinea* leaves. The RF loss through the leaves was measured for different stages of drying. The results showed that there is a nonlinear relationship between effective water path (EWP) in mm and RF loss in dB. It can be concluded that 2.4 GHz frequency radio waves can be used to predict the water content inside eucalyptus leaves ( $0 < \text{EWP} < 14$  mm;  $\text{RMSE} \pm 0.87$  mm) and demonstrates the potential to measure the water content of whole trees.

## Keywords

Radio Attenuation, Leaves, Water Content, Path Loss, Vegetation Depth

## 1. Introduction

Forests, which today cover 30 percent of the world's land surface, are being rapidly and directly transformed in many areas by the impacts of expanding human populations and economies. Less evident are the pervasive effects of ongoing climatic changes on the condition and status of forests around the world.

Recent examples of drought and heat-related forest stress and dieback are being documented from all forested continents [1].

Eucalypts are iconic Australian forest trees. The Eucalyptus forest type is by far the most common forest type in Australia covering 101 million hectares, which is 77% of Australia's total native forest area [2]. The prolonged drought experienced in southern Australia between 1996 and 2010 (the Millennium Drought) caused widespread mortality and secondary insect attack in both eucalypt native forests and pine plantations [3]. Species composition has also changed in response to prolonged lower rainfall [4]. Since the mid-1990s, mainland southeast Australia has experienced an 11 percent reduction in April-October rainfall. Drought makes vegetation more flammable, and therefore more likely to support extreme bushfire behaviour [1].

Water stress affects plant growth and development due to reduction in photosynthetic activities [5] [6] [7] and hence affects forest productivity [8] [9]. Canopy leaf wilting is considered an important visible symptom of drought, when water loss by transpiration is greater than absorption by the roots [10] [11]. The detection of plant water status is important for monitoring the physiological status of plants, and the assessment of drought and fire risk in natural plant communities, and the irrigation scheduling of crops [12] [13]. Although field sampling of single leaves and shoots provides the most accurate assessment of plant water status, such methods are not feasible when estimates are required for large areas of vegetation [14].

Previous studies on understanding the interaction between radio waves and vegetation generally have been directed towards the engineering of reliable radio communication networks in that environment. Both empirical [15] [16] [17] [18] [19] and analytical models [20] were developed for radio frequency (RF) loss through vegetation, but these models do not consider the amount of water inside the vegetation. Radio transmission within wireless sensor networks could serve a dual purpose. Quite apart from sending data between sensors in the network, the radio signals themselves could be sensing the medium in the signal path.

For a lossless medium between the transmitter and the receiver, the maximum signal is received via a direct wave. When there is no obstruction between transmitter and receiver, a free-space model is used to estimate the decline in signal strength with the distance that arises from the radio wave spreading out, the so-called free-space loss. This simple model does not consider the influences of the earth surfaces nor considers the effect of obstacles such as trees, vegetation, buildings, uneven walls, lamp posts between the transmitter and the receiver [21]. Radio waves propagating through any type of material may experience further attenuation (also called excess loss) because of reflection, refraction, diffraction, absorption and scattering.

Signal attenuation occurs as the signal wave passes through a single tree, a group of trees or a forest due to absorption and scattering by the discrete ele-

ments such as the branches, twigs and leaves [15] [22] [23]. Apart from the signal attenuation, fading (variation in signal strength with time) is another issue caused by multiple path propagation due to vegetation as an obstruction. This results from constructive or destructive interference depending on the relative phase of the signals arriving at the receiver. There are other factors such as operating frequency, the distance between the transmitter and receiver and their position relative to vegetation, antenna height, polarization, temperature, humidity, terrain and weather, which can affect the signal transmission.

A canopy of a tree or trees in a path of radio signal path provides stronger attenuation compared to trunks [24] [25] [26]. The attenuation can change substantially due to growth and development stages including leaf loss, fruit growth, etc. [15] [19] [27] [28] [29]. In most forest environments, the fruit size will be much smaller compared to the leaf size and the effect of the fruit on radio propagation might be negligible compared to leaves. But the fruit size might have an additional effect in the agricultural environment, where the canopy density increases with fruit growth. Previous studies on radio propagation through vegetation have revealed that attenuation at any frequency is greater for trees in-leaf compared to trees without leaf [16] [18] [19] [30] [31] [32] [33] [34]. This suggests that leaves are the strongest contribution to attenuation.

If the size of the foliated obstruction through trees and the wavelength of the propagating wave are similar then signal attenuation is observed to be higher [35] because of diffraction and scattering caused by the tree along the propagation path [36].

Le Vine and Karam [37] calculated the attenuation associated with a vegetation canopy using a “discrete scatterer” model, where the vegetation canopy is presented by a sparse layer of discrete, randomly oriented particles such as leaves, stalks, branches, etc. over a homogeneous ground plane (soil). They found that, for frequencies up to 5 GHz, the attenuation varies almost linearly with plant water content over the range 0.2 to 0.5 (by volume). But for optical frequencies, the attenuation is relatively independent of both water content and frequency. Nakajima, Ohyama, Juzoji and Ta [38] measured the RF attenuation of individual leaves at 5, 10 and 20 GHz in a waveguide. They also imaged a live tree by measuring RF attenuation at 10.5 GHz concluding that microwave attenuation by tree foliage should have a strong link to water content in the leaves. The dependency of attenuation on water content is through the dielectric constant which is highly dependent on the water content inside the material. Furthermore, moisture on the surface of leaves of the trees absorbed the signals and caused more attenuation [32] [39] [40] [41].

Radio waves interact strongly with water and eucalyptus leaves are no exception. Rather than treat the attenuation of radio waves by a water-laden eucalyptus canopy as something that must be accounted for and mitigated, the goal of this study is to investigate the feasibility of using the attenuation of radio waves to predict the water content of the eucalypt leaves themselves. In order to test the

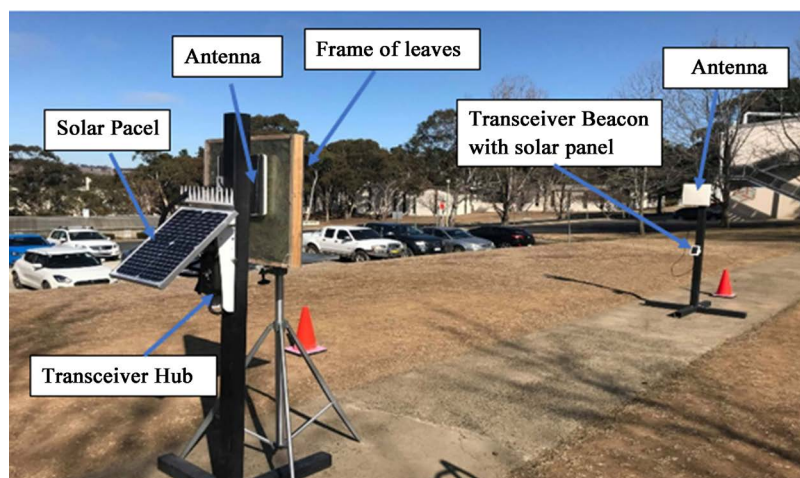
hypothesis that radio wave attenuation can be used to estimate water content of vegetation, this initial investigation examines a simplified system involving a controlled presentation of moisture-laden eucalyptus leaves to propagating radio waves.

We postulate two simplifying assumptions: 1) RF loss relates directly to the total amount of water in the signal path rather than its distribution or density; 2) The leaf material is homogeneous on a wavelength scale. Consequently, we propose that, with regard to its effect on RF loss, the amount of water can be expressed as an effective water path (EWP), equivalent to the thickness of a sheet of 100% water with the same mass.

## 2. Method

### 2.1. Experiment Site and Equipment Used

All the experiments were carried out at The University of New England main campus located in Armidale, New South Wales, Australia (latitude 30.4867°S and longitude 151.6430°E). Two flat-panel, phased-array directional antennas (ARC Wireless Solutions, USA, PA2419B01, 39.1 cm × 39.1 cm × 4.3 cm) were used, one as a transmitter connected to a transceiver Beacon (Dosec Design, Australia, EnviroNode Beacon) and the other as a receiver connected to a transceiver hub (Dosec Design, Australia, EnviroNode Hub) operated at 2.4331 GHz frequency. The antenna had a gain of 19 dBi, front-to-back ratio of >30 dB and 3dB beamwidth of  $\pm 9^\circ$ . The antennas were placed outside, facing each other at 6.10 metres apart. A constant transmitted power of 100 milliwatts was used. The hub measured and logged the RSSI (received signal strength indicator, dBm) to a removable SD card at 1 minute intervals. The experimental set-up is shown in **Figure 1**.



**Figure 1.** Experimental set-up. Two flat-panel antennas were mounted facing each other 6.10 m apart. Frame contains the leaves being tested, that was mounted on a tripod immediately in front of one antenna. Solar panels for electrical power are also visible. The RSSI (dBm) was recorded to a removable SD card inside the transceiver Hub every minute.

## 2.2. Verifying the Experimental Set Up

Some preliminary measurements were made to verify the experimental set-up. A wooden frame covered, front and back, with 5 mm clear acrylic sheets was used to hold the leaves to be tested. In order to confirm that only radio waves propagating directly through the wooden frame were received by the receiver (*i.e.* no multipath signals), a metal sheet, impenetrable to radio waves, was temporarily attached to the front of the frame. The position of the frame relative to the transceivers was then optimised such that the RSSI was below the minimum measurable power level for our equipment ( $-80$  dBm).

In order to measure a potential effect of the wooden frame itself, each of the empty frames was positioned between the transceivers and the RF signal loss, relative to no frame in place, was measured. Irrespective of frame size, the RF loss through the empty frame was confirmed to be below the measurement resolution of 0.1 dB, which indicated that any loss associated with the frame of leaves would be solely due to the presence of the contained material inside.

## 2.3. Measurements with Leaves

A wooden frame (inner dimensions 600 mm  $\times$  560 mm  $\times$  42 mm) was completely filled with freshly-plucked, turgid *Eucalyptus laevopinea* (silver top stringybark) leaves such that there was no visible gap between the frame and leaves when the frame is flipped over. The filled frame was then weighed. The RSSI (dBm) for no obstruction between the transceivers was measured for 3 minutes and then the frame filled with leaves was placed on the stand and signal strength was again measured for 3 minutes. The difference between the time-average RSSI with and without frame in place was converted to a time-averaged RF loss associated with the leaves. The sequence of frame and no frame measurements was repeated three times to provide a measurement average. The RF loss ( $L$ ) associated with the sample of leaves was then calculated using,

$$L(\text{dB}) = \text{RSSI}(\text{no frame}) - \text{RSSI}(\text{frame} + \text{leaves}). \quad (1)$$

Following the RSSI measurements with and without the frame in place, the leaves were removed from the frame and oven-dried in a vacuum oven at a temperature of 60°C and 80 kPa (60 cmHg) vacuum gauge pressure for one hour. As condensation and the temperature of the transmitting material effects radio wave transmission, the hot leaves were then spread on a table surface to both cool down and allow residual water vapour to dissipate rather than condense. The frame was then refilled with the cooled leaves and weighed. The frame containing the now partially dried leaves was then placed on the stand at the experimental site and the process of measuring the RSSI was repeated.

The process of partial drying and remeasuring the RSSI was repeated until no further weight loss from drying was achieved (*i.e.* leaves were considered dry). At this point, the leaves are yellowish and brownish in colour and were brittle.

At this end point, the mass of the water ( $m_w$ ) in the freshly plucked and each partially-dried, leaf sample was retrospectively calculated from the known mass

of the leaf samples and the final dry weight of the leaves.

The measurement sequence was repeated for frame thicknesses of 63 mm, 105 mm, 147 mm and 195 mm. The densities of the material before drying in each frame were in the range 0.33 to 0.39 g/cm<sup>3</sup>.

#### 2.4. Calculation of Effective Water Path (EWP)

The data from the hub's SD card was transferred to an Excel file for analysis. For each leaf sample, the difference between the weight of the frame filled with leaves and when empty yields the weight of the leaves in kg. The weight of water inside the leaves in each of the leaf samples was then calculated by subtracting the weight of the dry leaves (final leaf state after successive partial drying steps) from the weight of leaves at different stages of drying.

The radio wave passes through vegetation depth,  $d_v$ , containing a distributed mass,  $m_w$ , of water (kg). In order to quantify the equivalent amount of water affecting the radio wave, we define the effective water path (EWP) as the thickness of a sheet of 100% water with the same mass. If the dimension of the frame are  $d_v$ ,  $x$ , and  $y$  then the volume of the frame  $V$  (m<sup>3</sup>) is simply

$$V = x \times y \times d_v. \quad (2)$$

And the water mass is

$$m_w = \rho_w \times \text{EWP} \times x \times y, \quad (3)$$

where,  $\rho_w$  is the density of pure water 1000 kg/m<sup>3</sup>. Hence,

$$\text{EWP} = \frac{m_w \times d_v}{\rho_w \times V}. \quad (4)$$

The weight of water inside the leaves was converted to an effective water path (EWP), expressed now in mm, using Equation (5)

$$\text{EWP} = \left( \frac{m_w \times d_v}{\rho_w \times V} \right) \times 1000. \quad (5)$$

Note that both  $m_w$  and EWP will be zero for dry leaves.

### 3. Results and Discussion

**Figure 2** shows the RF loss through leaves for five different thicknesses of the frames (42 mm, 63 mm, 105 mm, 147 mm and 195 mm) as functions of EWP. The maximum measured loss is 30 dB and any loss higher than this was not measurable with the experimental equipment. It was observed from the data that the RF loss did decrease with reduction of effective water path length associated with drying. The RF loss for completely dried leaves was lower than that for leaves partially dried to any extent for each frame thickness tested, but it was not zero. While most of the RF loss is associated with water in the leaves, there is still some residual RF loss when the leaves are completely dried.

It can be seen from **Figure 2** that the RF loss is greater if the vegetation depth is greater, even if the total amount of water in the radio path is the same (and

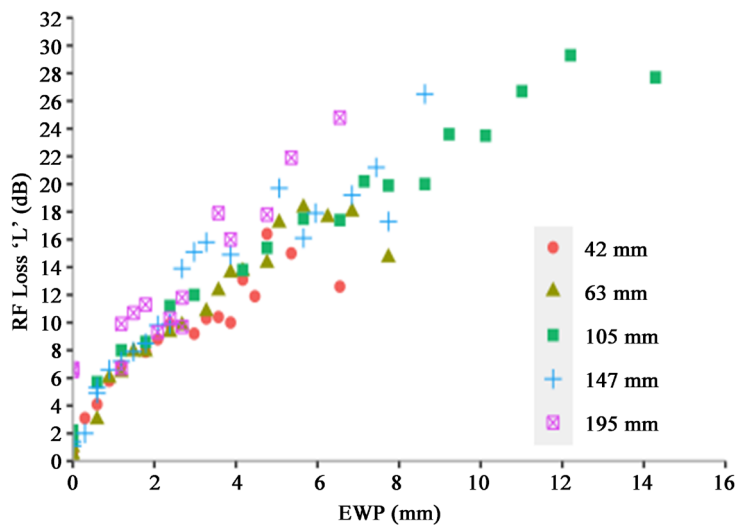
therefore the density of the contained water is less). Furthermore, when all the free water was removed by drying, the RF loss of the dried material was not zero and had an increasing trend with vegetation depth. These results are consistent with some RF loss being associated with the non-water part of the leaf material that is in addition to the generally greater loss due to water.

The result of a multiple regression model fit to the experimental data is

$$EWP = 0.007L^2 + 0.234L - 0.01d_v, \tag{6}$$

( $r^2 = 0.92$ ; Range = 0.0 - 14.3 mm; S.E.  $\pm 0.87$  mm, significant  $p < 10^{-5}$ ), where, EWP and  $d_v$  are in mm and  $L$  is in dB. The same units apply for the models in **Table 1**. The RF loss  $L$  linear term has the greatest predictive value. The nonlinear  $L^2$  term and the vegetation depth  $d_v$  term have a relatively small effect on the prediction. This is illustrated by **Table 1** which compares the standard error of the predicted EWP for some simpler regression equations.

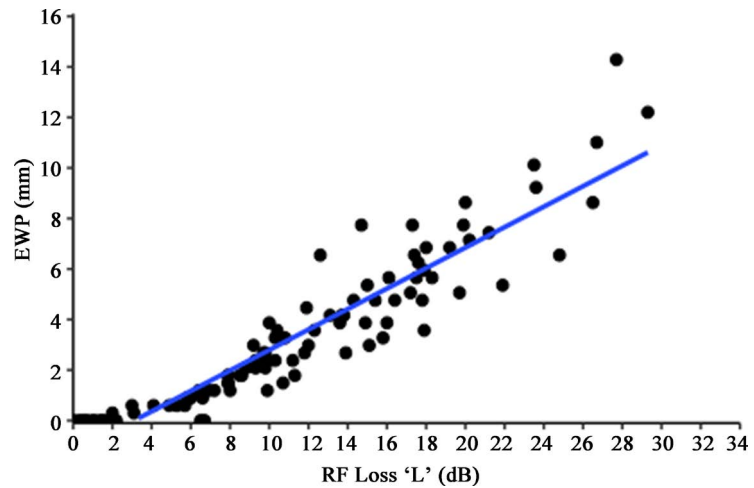
The standard error of the predicted EWP by the full equation (0.87 mm) is moderately better than that for an equation containing only  $L$  (1.26 mm). **Figure 3** shows the predicted EWP calculated from RF loss and vegetation depth using



**Figure 2.** RF Loss (dB) versus effective water path length (mm) during drying of eucalyptus leaves, for five frame thicknesses. Legend shows the thickness of the frame (vegetation depth  $d_v$ ). Data points corresponding to fresh leaves are generally toward the upper right with both the RF loss and EWP generally declining as drying progressed.

**Table 1.** Multiple regression models to predict EWP.

Predictor Variables	Model	$r^2$	SE (mm)	
Full Equation	$EWP = 0.007L^2 + 0.234L - 0.01d_v$	0.92	$\pm 0.87$	$p < 10^{-5}$
$L$ and $d_v$	$EWP = 0.423L - 0.011d_v$	0.90	$\pm 0.97$	$p < 10^{-6}$
$L$ and $L^2$	$EWP = 0.008L^2 + 0.203L$	0.89	$\pm 1.02$	$p < 10^{-4}$
Only $L$	$EWP = 0.405L - 1.26$	0.87	$\pm 1.12$	$p < 10^{-6}$



**Figure 3.** Predicted effective water path length (EWP) from Equation (6) compared to experimental values (circles) with all measurements pooled. Line shows prediction.

Equation (6) compared to the experimental EWP calculated from the change in weight of frame of leaves during drying.

RF loss through vegetation such as leaves and trees is strongly related to the amount of water in vegetation, which is consistent with the previous modelling by Le Vine and Karam [37] and studies conducted by Nakajima, *et al.* [38].

For our measurements at 2.4 GHz frequency, there is a nonlinear relationship between EWP and radio loss in dB. The dependence of RF loss on water content is through its permittivity. As RF loss changes non-linearly with permittivity, a nonlinear relationship seems plausible. This result can be compared to the previous modelling [37] in which the attenuation associated with a vegetation canopy is calculated using a discrete scatterer model. The nearest radio frequency to 2.4 GHz (used in our experiments) in their results is 1 GHz. A comparison of the trends can be made but not the RF loss in absolute terms because it is strongly affected by frequency. They predicted that the attenuation varies almost linearly with moisture content of vegetation.

Other than moisture content inside the leaves and the vegetation depth, the density of packing of leaves inside the frame might be a factor causing the radio loss. This factor couldn't be verified with the experiment we carried out, but we hope that doing an experiment with a whole tree and comparing the results can verify whether density of packing of leaves (or distribution or orientation of the leaves in case of a tree) is a factor or not.

Since the transceivers used can measure RF loss up to 30 dB, the results are only valid for EWP up to 14 mm. This can be improved by using other transceivers which measures loss higher than 30 dB.

We placed the frame of leaves close to the antenna in order to ensure that radio waves being measured did indeed travel through the leaves rather than some spurious path (via reflection from the ground, for example). This is in the near field of the antenna. Analysis of radio wave propagation is complicated in the antenna's near field and it would be preferable to place the material being tested



further from it. To allow for the diverging radio beam, the size of the frame must be then increased and soon becomes impractical. For measurements on whole trees, however, this problem is resolved due to their greater size.

The result from this paper was further compared with our RF model through vegetation in Peden, Bradbury, Lamb and Hedley [42].

#### 4. Conclusion

It can be concluded from the results above that there is a nonlinear relationship between radio loss in dB at 2.4 GHz and effective water path (EWP) of Eucalyptus leaves. EWP is the dominant factor compared to vegetation depth. This work raises the possibility of estimating the water content of whole trees based on the radio loss and size of the tree. Further work is being carried out by us to predict the water content of a whole tree using RF loss.

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#### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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