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Wide Band Permittivity Measurements of Palm (*Phoenix Canariensis*) and *Rhynchophorus ferrugineus* (*Coleoptera: Curculionidae*) for RF Pest Control

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ABSTRACT

Rhynchophorus ferrugineus Oliv., known as the red palm weevil (RPW), has quickly spread in Southern Europe, infesting and destroying an increasing number of palms, particularly the *Phoenix canariensis* ones. Of the various techniques suggested for treating the palms, high power microwave applications are considered an attractive, eco-compatibile solution. However, in order to correctly design the exposure system, a knowledge of the electromagnetic properties of the materials involved is required. In this paper, we present a broad-band electromagnetic characterization in the 0.4 -18 GHz frequency range of the tissues (both healthy and damaged) of the *P. canariensis*, with different moisture content, and of the *R. ferrugineus* in different stages (larva, pupa and adult). The palm tissues were shown to contain a high water content and a dielectric model of the vegetation was applied to the experimental data in order to estimate the volume fraction of free water and of the bulk vegetation-bound water mixture as well as the ionic conductivity of the free-water solution.

KEYWORDS: Dielectric Heating, Permittivity Measurements, Pest Control, R*hynchophorus ferrugineus* and *Phoenix canariensis* palm.

INTRODUCTION

The dielectric properties of vegetation play a central role in several types of electromagnetic applications such as remote sensing [Franchois *et al.*, 1998], wood treatment [Torgovnikov and Vinden, 2010], radio frequency pest control [Hansen *et al.*, 2011]. Many studies are devoted to collecting permittivity measurements of plants [Koubaa *et al.*, 2008] and agricultural products [Wang *et al.*, 2003; Nelson and Bartley, 2000; Kraszewski and Nelson, 2004]. The aim of this paper is to describe the permittivity of the *Phoenix canariensis* palm and that of the Red Palm Weevil (RPW), *Rhynchophorus ferrugineus* (Olivier, 1970) (Coleoptera: *Curculionidae*). These data are of great importance to the study of the use of microwaves in RPW pest control.

In order to clarify the importance of RPW pest control, it is useful to recall that it is the major pest as regards both ornamental and income palms (i.e. coconut, date, oil and sago palms) all over the world. It is native to Southeast Asia and is reported to attack over 20 palm hosts [PQR, 2012]. It is found in Asia, Africa, and, more recently, Europe and United States [OEPP/EPPO, 2008].

The RPW has moved from Africa to the Mediterranean and Carribean Basins mainly because of the movement of infested planting material. In Southern Europe it has quickly spread thanks to the absence of natural enemies, infesting an increasing number of *Phoenix canariensis* (Canary Island Date Palm). These ornamental palms are grown in Southern Europe and along Mediterranean shores as long-living, urban trees and they are common in the historic downtowns of many cities. Thus, pest control is the concern of public administrations, private owners and professionals (nurserymen, landscapers, business parks) that have to face the costs of treatment in order to reduce the damage done which includes a decline in the attractiveness of the old-town parts of cities as tourist attractions.

Several control methods have been applied against this pest as part of an integrated pest management strategy.

The EU commission strongly recommends increasing the use of non-chemical methods as much as possible and promotes new research and action plans [2010/467/EU]. Taking into account these observations, the use of radio-frequency or microwave electromagnetic fields is extremely appealing [Ali, 2003], [Ali *et al.*, 2010].

Microwave (or dielectric) heating applications are increasingly used in environmental engineering [Jones *et al.*, 2002]. A number of fields have been evaluated including green chemistry [Varma, 2013], waste processing [Appleton *et al.*, 2005], thermochemical biomass-conversion [Dutta *et al.*,2013], mineral processing and activated carbon regeneration [Menendez *et al.*, 2010].

Benefits such as reduced energy consumption, process time savings, increased process yield and environmental compatibility are exploited and the use of microwaves could be suitable for limiting the spread of RPW.

Recently, our multi-disciplinary team of researchers in entomology, agronomy, physics and engineering has been involved in the study of palm weevil sanitation by means of microwave thermal treatments within a framework that Regione Campania has developed to face this emergency. Encouraging, preliminary results were obtained using microwave heating at a frequency 2.45 GHz [Massa *et al.*, 2011]. On the basis of these data on the effectiveness of a microwave treatment of infested palms, the group has undertaken a more rigorous and systematic analysis of the problem, starting with an exhaustive study of the electromagnetic properties of both plant and insect.

To the authors' best knowlewdge, palm and weevil (larva) permittivity values have only been reported at a frequency of 2.45 GHz [Massa *et al.*, 2011], and a large bandwidth description is absent in the literature. Knowledge of permittivity at different frequencies is interesting since it allows the investigation of the effectiveness of several frequencies in the ISM (Industrial, Scientific, Medical) bands.

This paper presents the results of an extensive measurement study of the complex permittivity of the *P. canariensis* palm tissues and the palm weevil in different stages of its life. Dielectric characterization of samples under test has been carried out in the 0.4 GHz - 18 GHz frequency range. The data provide useful observations on the feasibility of a microwave applicator as a treatment for infested palms.

RPW ISSUE AND PEST MANAGEMENT

It is now worth recalling some aspects of the RPW infestation.

RPW (Figure 1, A) is a strong flier. In general, females lay eggs in holes, made with their rostrum, in wounds, cracks and crevices on the trunk from the collar region near the roots to the base of frond petioles/axils near the crown. A single female lays 58–531 eggs which incubate for 1– 6 days before hatching into whitish-yellow larvae (grubs, Figure 1, B) which then live for 25–105 days. The grubs chew the plant tissue and move towards the interior of the palm, leaving behind chewed-up frass (plant fibers), which have a characteristic fermented smell. Frequently, the frass protrudes through the holes on the infested stem/petiole. Thus neonate larvae bore into the palm core and, upon completion of development (seven to twenty larval stages were observed), move back to the base of the fronds to pupate. The completely developed grubs pupate in a cocoon (about 80 mm x 35 mm) made from chewed fibres (Figure 1, C). The pupal development period ranges from 11 to 45 days. A new generation emerges and these adults may remain within the host and reproduce until the palm dies. The life cycle of the pest may vary from just 45 days to 139 days. Several overlapping generations comprised of different stages of the insect may be seen inside an infested palm. More detailed descriptions of RPW issues and management are reported in [Failero, 2006; El-Mergawy *et al.*, 2011].

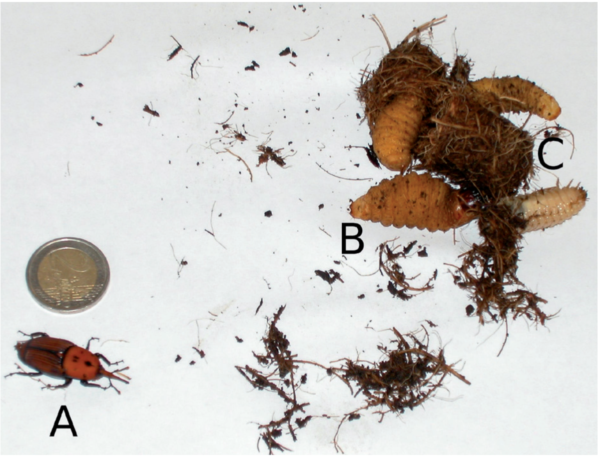

Figure 1. Different stages of *Rhynchophorus ferrugineus*. A: adult; B: larvae; C: cocoon.

The main components of the various control methods adopted to face this pest are: phytosanitation, use of pheromone traps for adult monitoring and mass trapping and biological and chemical techniques. Phytosanitation involves cutting down and burning infested palms while the trap technique exploits the RPW's highly developed sense of smell. Traps baited with synthetic pheromone, ethyl acetate and a natural odour produced by the fermentation of sweet plant tissues attract RPWs, above all females, and contribute to the mass removal of the adults. Biological pest control relies on the use of natural enemies, either entomophagous arthropods (predators and parasitoids) or entomopathogenic microorganisms (nematodes, bacteria, fungi and viruses). Finally, chemical control against RPW mainly consists of the repeated application of large quantities of pesticides used in various ways and designed to limit and contain the spread of infestation: protecting wounds, soil application, spraying, localized direct injections into the palm trunk and fumigation. There are, however, major concerns regarding the environmental pollution caused by these treatments, especially in public areas where ornamental palms are grown.

Dielectric heating (DH) is proposed as an "eco-friendly green protocol". An important key in developing successful dielectric thermal treatments is to balance the complete eradication of the insects with minimized thermal impact on plant tissues.

Besides the electromagnetic characteristics of the materials involved in the microwave heating process, the thermal treatment requires the temperature the targeted insects will be killed to be known.

Concerning this point, we have reported an estimation of the time needed to kill 100% of the larvae and adults in an incubator at a fixed temperature varying between 50 ˚C – 80 ˚C. Results indicate that the adult insects are much more sensitive to heat than the larger larvae (weight 5-6 g), at 50 ˚C adults are killed after 20 min, larger larvae after 30 min, while 15 min are enough to cause the death of smaller larvae (2-3 g). At 80 ˚C less then 5 min is sufficient to kill RPW regardless of what stage of their lives they may be at. Furthermore, some preliminary experiments show that it is possible to reach the required temperatures without damaging the palm [Massa *et al.*, 2011].

MEASUREMENT METHOD

The electromagnetic characterization of materials is a widely studied problem, and there are several methods available in the literature [Metaxas, 1996; Baker-Jarvis *et al.*, 1993]. Among them, the methods using truncated coaxial cables as probes are particularly suitable for the wideband permittivity characterization of solids and liquids [Baker-Jarvis *et al.*, 1993; Anderson *et al.*, 1994; Misra *et al.*1990; Migliore, 2000; Panariello *et al.*, 2001; Romeo *et al.*, 2011] and, in particular for woods, fruits and foods [Nelson and Bartley, 2000; Nelson *et al.*, 1997; Wang *et al.*, 2003; Soproni *et al.*, 2012]. These methods are based on the measurement of the reflection coefficient at the tip of a truncated coaxial cable placed in contact with the material under test (see Figure 2) and connected to a Vector Network Analyzer (VNA).

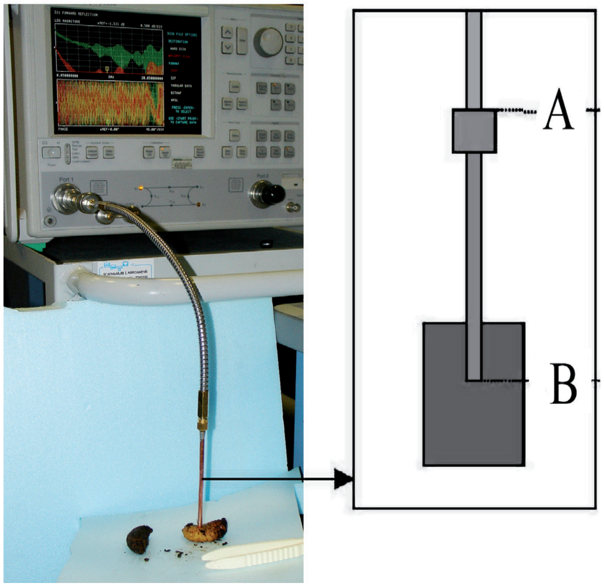

Figure 2. The permittivity measurement system. Left: truncated coaxial cable placed in contact with the SUT. Right: sketch of the cable and reference plane where the reflection coefficient is evaluated.

There are two key steps to this approach. The first one is the evaluation of the functional relationship between the reflection coefficient of the coaxial cable radiating toward a half-space, and the electromagnetic characteristics of the material filling the half-space. The second one consists of developing a suitable calibration technique able to retrieve the reflection coefficient at the tip of the cable (section B in Figure 2) from the measurements at the gate of the VNA (section A in Figure 2). All the proposed procedures implementing this method essentially differ as regards these two steps.

In our approach, we use, for the first step, the impedance of a truncated standard semi-rigid 50 ohm coaxial cable (diameters 2.2 mm and 3.6 mm) expressed in a rational form [Anderson *et al.*, 1994] and valid in the range 1-20 GHz. This expression allows the evaluation of permittivity in quite a simple way. Moreover, a satisfactory level of accuracy is achieved in the case of lossy media as expected in the case of biological samples [Panariello *et al.*, 2001].

As regards the second step, we used the calibration technique proposed in [Misra *et al.*, 1990], based on the description of the response of the coaxial probe using known loads. This method resembles the standard error correction techniques used in VNA and requires terminating the probe on three known loads; in our case, a short circuit (s), an open circuit (o) and a liquid (l). With reference to Figure 3, the three scattering coefficients S_{11}, $S_{12}*S_{21}$, S_{22} [Collin, 2001] are obtained by inverting the three non-linear equations relating the measured reflection coefficients Γ_{ms}, Γ_{mo}, Γ_{ml} (wherein m stands for 'measured' value at the section A of Figure 3) with the reflection coefficients at the tip of the probe, Γ_s, Γ_o,Γ_l (i.e. at the Section B of Figure 3) obtained by the rational function interpolation formula. The advantage of this approach is that it is able to correct, at least partially, errors that can affect the measurements due to the cable response as well as the unavoidable representation error of rational function interpolation formula or other impedance formulas of the chosen truncated cable [Misra *et al.*, 1990].

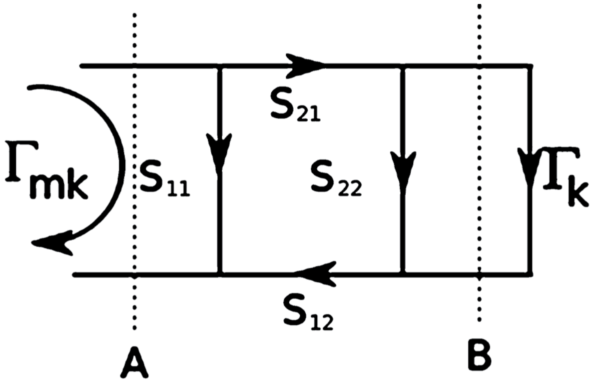

Figure 3. Probe calibration: flow-graph of the microwave signal; Γ_{mk} is the measured reflection coefficient (section A in Figure 1), Γ_k is the reflection coefficient at the tip of the probe (section B in Figure 1); k indicates the load used in the calibration process (k=o for open circuit, k=s for short circuit, k=l for known liquid).

EXPERIMENTAL SETUP

A sketch of the experimental setup is depicted in Figure 2. A probe, obtained using a truncated coaxial cable (UT141, 3.6 mm external diameter), was placed in contact with the sample under test (SUT). The other end of the coaxial cable was connected to the VNA (Anritsu 37347C) by means of a semi-rigid coaxial cable (Wiltron 670K50-1).

Settings were made to provide measurements at 1601 frequency points from 400 MHz to 18 GHz. The VNA was calibrated with a high-precision calibration kit (Anritsu 3650) using open, short, and matched load prior to the calibration of the open-ended coaxial-line probe with measurements on air (o), with a short-circuit block (s), and distilled water (l) at 20 °C.

RESULTS

In order to have a description of the electromagnetic behavior of media involved in the heating process, the evaluation of the permittivity of both the palm tissues (healthy and damaged) and that of the weevil in different stages (adult, puparia chamber, larva) were carried out. In addition, the moisture content contribution in the palm was considered; humidity being a parameter that can change during the thermal treatment. Results for the frequency dependence of the permittivity and the skin depth are shown in plots where the mean values for 10 measurements carried out in different positions of the sample are reported.

Palm Tissues

The permittivity results from healthy and damaged palm tissues are reported in Figures 4 and 5 respectively. The damaged tissue consists of plant fibres chewed up by the larvae combined with the plant tissues, and, from a biological and mechanical point of view, it is very different from the healthy tissue because of the joint effect of the RPW and its bacteria. The percentage of the volume occupied by these tissues in the palm strongly depends on what stage the infection has reached.

Bearing in mind the above observations, in our measurements, moisture content was determined by drying the sample in a forced-air drying oven at 80 °C for 2 h, 4 h or 24 h and then weighing it on an analytical balance to determine its mass.

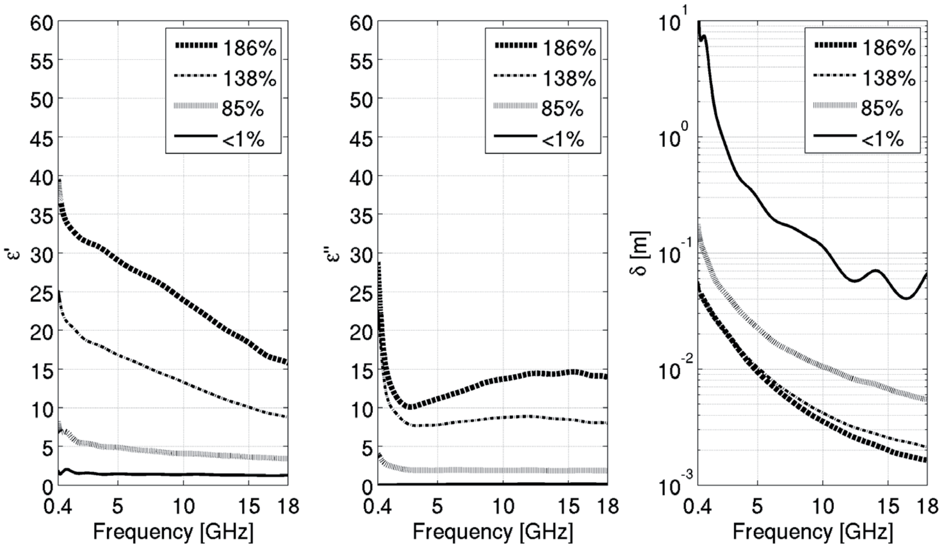

Figure 4. Permittivity mean value of healthy tissue of *P. canariensis* palm with different moisture content; from left to right: real part of the permittivity, imaginary part of the permittivity, penetration depth δ [m].

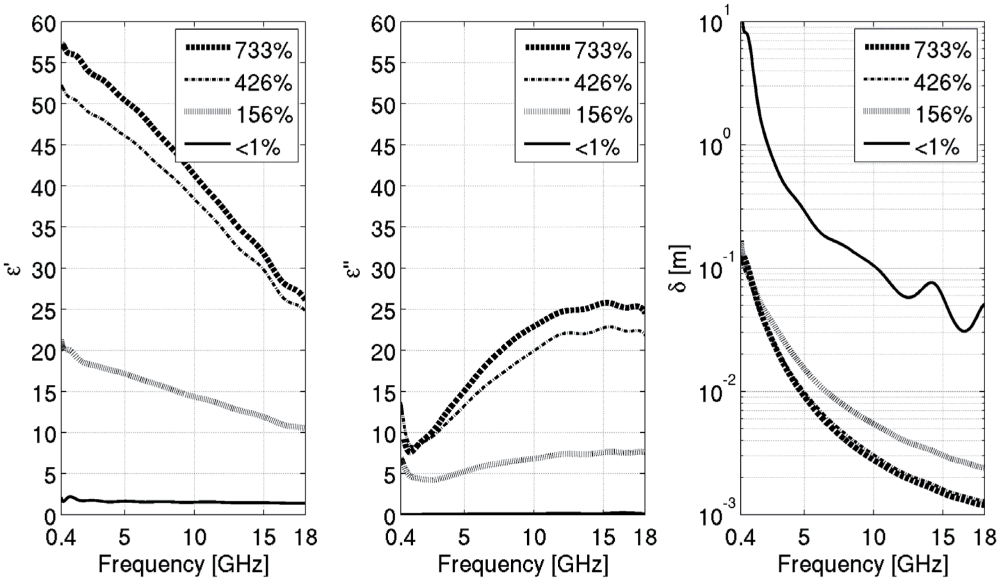

Figure 5. Permittivity mean value of rotten tissue of *P. canariensis* palm with different moisture content; from left to right: real part of the permittivity, imaginary part of the permittivity, penetration depth δ [m].

The moisture content was evaluated as MC = (M_{water}/M_{sample}) x 100, where M_{water} is the mass of water in the sample and M_{sample} is the mass of the oven-dried sample.

Operationally, the moisture content of the given piece of palm was calculated by MC= $((m_{wet} - m_{dry})/m_{dry})$ x 100, where m_{wet} is the mass of the specimen at a given moisture content and m_{dry} is the mass of the oven-dried specimen [Glass and Zelinka, 2010].

The highest water content refers to the specimen measurements taken about one hour after being cut from the living plant. In order to prevent loss in humidity during the transport form the field to the laboratory, the specimen was stored in a watertight plastic container.

The samples were held at ambient temperature (21°C) during all of the permittivity measurements.

In Figures 4 and 5, we have also reported the electric field penetration depth δ versus frequency (*f*) calculated as

$$\delta = \frac{c\sqrt{2}}{2\pi f\sqrt{\varepsilon'\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}}$$

where c is the speed of light, and ε=ε'-jε" is the complex permittivity relative to that of free space ε_0= 8.86 10^{-12} F/m [von Hippel, 1954].

Particularly, the parameters versus the MC in the 400 MHz – 18 GHz frequency range are shown, being the highest water content 186% and 733% respectively for the healthy and damaged palm tissues.

The data indicate that both the damaged and the healthy palm tissues have a fairly high water content. As result, the penetration depth in the palm is in the order of a couple of centimeters at the 2.45 GHz frequency and increases significantly at lower frequencies. The values measured for the oven-dried specimens concord well with those expected for bulk vegetable material in the range 0.5 – 20 GHz: 1.5 ≤ ε' ≤ 2, ε" ≤ 0.1 [Ulaby and El-Rayes, 1987]. As in other kinds of plants, both the real and imaginary parts of permittivity decrease with decreasing MC. In addition, both the MC and permittivity data were similar to those reported for sapwood [Franchois *et al.*, 1998, Koubaa *et al.*, 2008].

However, it has to be observed that the damaged tissue behaves quite differently compared to the healthy tissue. Notice that if we compare tissue results at the same initial stage (i.e. 733% damaged tissue compared to 186% healthy tissue) the damaged tissue has much higher permittivity. This is probably due to the fermentation and bacteria present in the infected zone that is typically more soft and fibrous compared to healthy tissue and which therefore retains a higher water content. Nevertheless, the penetration depth always remains of the order of a couple of centimetres at 2.45 GHz, and increases for lower frequencies.

Dielectric Model for Palm Tissues

On the basis of the data collected in the previous section, the dielectric model of vegetation proposed by Ulaby [Ulaby and El-Rayes 1987] was considered. To this end, the permittivity of vegetation was assumed to be a mixture of three components: 1) a non-dispersive residual component (ε_r), 2) a free water component, 3) a bulk vegetation-bound water component:

$$\varepsilon_v = \varepsilon_r + v_{fw}\left(4.9+\frac{75}{1+jf/18}-\frac{j18\sigma}{f}\right)+ v_b\left(2.9+\frac{55}{1+\left(jf/0.18\right)^{0.5}}\right)$$

where v_{fw} and v_b are the volume fraction of free water and of the bulk vegetation-bound water mixture, σ is the ionic conductivity of the free-water solution, *f* is the frequency. The terms in parenthesis are the Debye equations relative to saline water and sucrose-water solutions.

By fitting the model to the measured data the values of v_{fw}, v_b, and σ for the different MC were obtained, assuming ε_r to be the measured value of the oven-dry specimen. Results are reported in Table I and in Figures 6 and 7 together with the measured behavior. As expected, the higher values of v_{fw} and v_b correspond to the higher MC; they decrease with the decreasing of MC and the decreasing rate of v_{fw} is larger than that of v_b.

Finally, measurements of the density (ρ) of the trunk were carried out. This is also a parameter related to the increase of temperature (ΔT) in the medium when

Table I. Parameters for the Ulaby's model for the palm tissues.

	MC	ε_r	σ [S/m]	v_{fw}	v_b
Healthy tissues	186%	1.5	2.00	0.308	0.415
	138%	1.5	3.25	0.150	0.387
	85%	1.5	3.25	0.025	0.155
Damaged tissues	733%	1.5	0.25	0.603	0.331
	426%	1.5	0.25	0.537	0.379
	156%	1.5	0.25	0.166	0.311

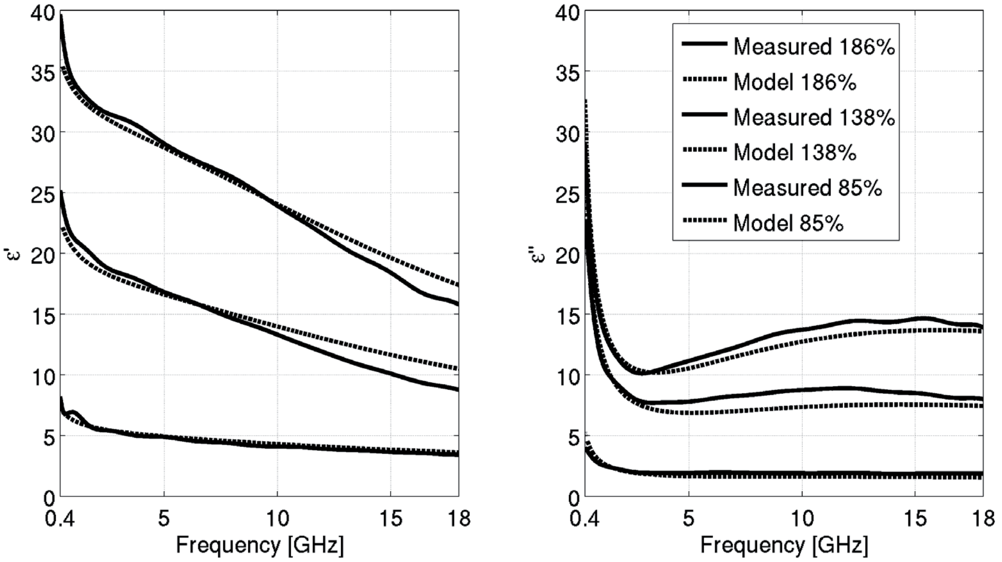

Figure 6. Comparison of the measured complex permittivity at different moist content and that from the Ulaby's model with the parameters of Table I for healthy tissues.

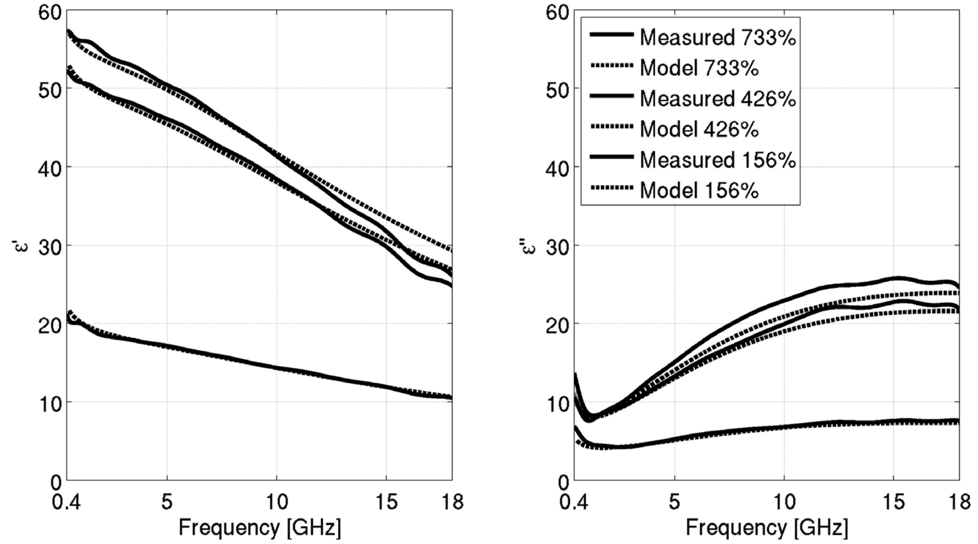

Figure 7. Comparison of the measured complex permittivity at different moist content and that from the Ulaby's model with the parameters of Table I for rotten tissues.

treated with radiofrequency or microwaves during a time interval Δt. In particular:

$$\frac{\Delta T}{\Delta t} = \pi f \varepsilon'' \varepsilon_0 \frac{|E|^2}{c\rho}$$

E is the electric field amplitude and c the specific heat. Three specimens of healthy palm were weighed with an analytical scale and the volume was derived by means of oil displacement in a 500 ml cylinder. The average density was 844 kg/m^3. Thus the time rate of initial temperature rises in the first few seconds of exposure, over which heat diffusion and convection can be assumed to be negligible [Moros and Pickard, 1999], can be estimated and is reported in Table II for ISM frequencies and in the case of an electric field amplitude of 1000 V/m .

Table II. Time rate of initial temperature rise in the case of 1000 V/m electric field in the healthy palm tissues.

	434 MHz	915 MHz	2450 MHz
ΔT/Δt [°C/sec]	0.099	0.118	0.199

RPW in the Different Stages of Development

In Figure 8, we can see the results of the permittivity measurement of the RPW in different development stages: larva, the pupal chamber, adult (Figure 1). The pupal chamber consists of partially digested palm tissue, and is, therefore, different from the damaged tissue described above, being more compact and free of any of the products of fermentation. These fibrous pupal cocoons are located at the base of the fronds near the surface of the palm trunk, and are employed in metamorphosis.

Such measurements were taken by placing the probe in contact with the surface of the SUT (Figure 2). It is interesting to note that the permittivity of the larva is very similar to the permittivity of the healthy palm tissue for the highest water content considered. The permittivity of the adult is, on the other hand, much lower due to the reduced water content of the insect at this stage compared to the larva. The comparison of the results obtained for the damaged tissues and pupal chamber highlights the fact

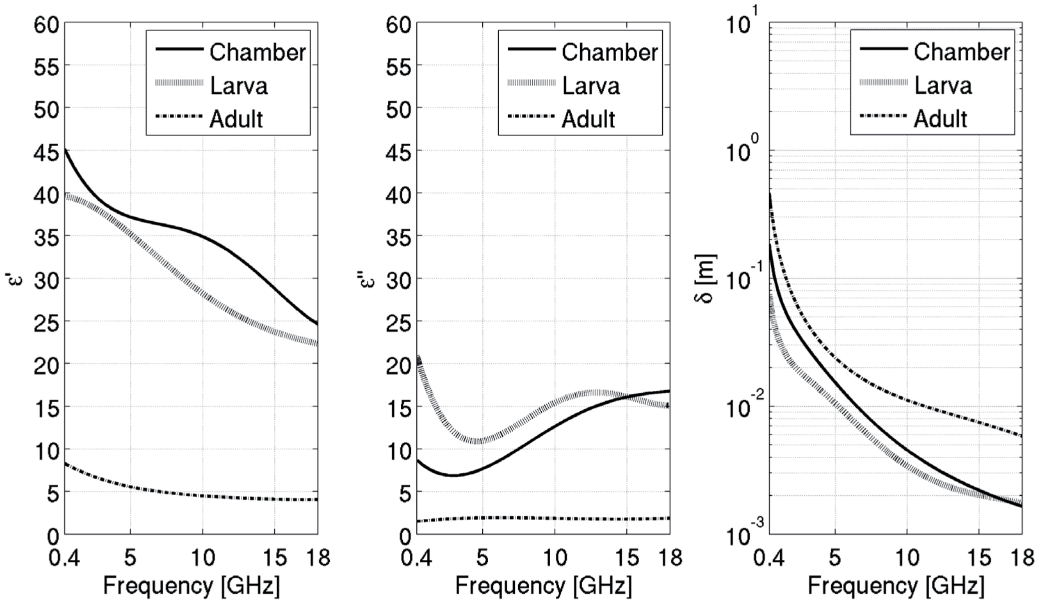

Figure 8. Permittivity mean value of *Rhynchoforus ferrugineus* (larva, adult and pupal chamber); from left to right: real part of the permittivity, imaginary part of the permittivity, penetration depth δ [m].

that the reduced presence of bacteria and fermentation products in the latter leads to a higher penetration depth in the chamber thus allowing the microwaves to reach the larva/adult depending on the stage of the metamorphosis. It is also worth noting that the penetration depth in the RPW is just of a couple of centimeters at 2.45 GHz, that is of the same extent of the size of the weevil.

FINAL REMARKS

In this work the dielectric heating of palms in order to control RPW pest diffusion has been considered. To this end, the permittivity measurements of healthy and damaged palm tissue as well as that of the RPW (larva, pupal chamber, adult) were conducted with the truncated-coaxial cable technique in the range 0.4-18 GHz. Results show a penetration depth of the order of a couple of centimeters at 2.45 GHz in the damaged palm, and a slightly lower depth in the healthy palm tissue. By applying Ulaby model to our data, the volume fraction of free water resulted higher than that of the bulk vegetation-bound water mixture in the damaged tissues, and the ionic conductivity of the free water solution is lower in the damaged tissues compared to that in the healthy tissues. These results are probably due to the soft and fibrous qualities and the different chemical composition (fermentation products) of the former. The similarity from an electromagnetic point of view, of the larvae and the healthy tissue means that is very difficult to use electromagnetic measurements to detect the first stage of the infection since the larvae contrast poorly with the healthy tissue. The situation changes when considering an advanced stage of the infestation since the presence of the damaged tissue (the contrast of which compared to the healthy tissue is significant) and the holes dug by the weevil can be detected. Unfortunately, such detection could be too late to save the plant. At the moment, the experts in this field are able to reveal the infestation by examining the leaves of the palm, thus microwaves or RF seem more suitable for sanitation of the palm in order to prevent the spread of the pest and to treat the plants in an eco-compatible way thereby reducing the need for pesticides. It should be noticed that, due the very high loss factor of palm tissues, only the external section of the palm is heated directly by the microwaves. However, in this area females lay eggs and neonate larvae are found as well as large larvae pupate, thus the thermal effect of RF could be particularly effective at the beginning of the pest process, (as a curative treatment for infected palm trees or as a preventive treatment in the production of "healthy" plants for planting), as well as to combat the weevil diffusion by eliminating the stage of pupal development when larvae change into weevils and a new generation of the pest emerges. As regards the losses in the damaged tissues, these are higher than in healthy tissues possibly due to the presence of products involved in the fermentation processes. In this area, temperatures of about 35 °C were observed, thus less electromagnetic energy is needed in order to achieve the lethal temperature of 50 °C, that should be sufficient to reduce or eliminate the larvae.

The results indicate the feasibility of these kind of treatments for pest control in palm trees.

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