Aeroponics monitoring and control system Using IOT

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Abstract— ***Aeroponic is the method of cultivating plants inside a conditioned air environment without the use of soil or water medium. This method grows plants suspended in a closed or semi-closed environment by spraying the plant's dangling roots and lower stems with nutrient-rich solution. Under controlled environment has a strong potential to improve plant's developmental stages, health, and growth. In the recent decade, aeroponic system is applied intensively for the purpose of growing corn in order to produce disease-free corn seed and in order to have a pesticides-free cultivation environment. It is also predicted that the aeroponic method will be able to lower corn farmer's cost of operation and increase their yields. The monitoring system was used to monitor the chamber's parameters such as temperature and humidity. meanwhile, the control system was used to manage actuators in delivering water and nutrients. Temperature and humidity data will be displayed on the LCD and be transmitted to computer to facilitate easier monitoring on the plant growing chamber. The overall system has been designed and implemented to receive user-defined setting points by using the keypad. Microcontroller system will automatically regulate actuators for distribution of water (pump and nozzle) and distribution of nutrients (ultrasonic mist maker, fan, and pump). The pH measurement results at various points showed that the nutrient (pH = 5.8) were successfully spread inside the growing chamber. The average measured-temperature and humidity of growing chamber during the water and nutrients delivery process are 19.6 °C and 83.3% RH, respectively, which meet the environmental requirements for corn to grow productively***.

***Index Terms*—** **Cavity resonators, dielectric measurements, microwave resonators, noninvasive, plant phenotyping, *RLC* equivalent circuit, volumetric measurements.**

I.INTRODUCTION

PLANTS are capable to synthesize organic molecules and to produce biomass determining crop yield for food, feed, and fibers. To increase plant biomass production, it requires deep knowledge of various physiological processes during plant growth. In this case, noninvasive methods of observation are useful and needed to achieve large sampling numbers to link the visible characteristics of a plant (phenotype) with the genetic background (genotype). In addition, a detailed time dependence of different parameters, such as water content, growth rate, and so on, during the whole period of plant development is key to investigate dynamic responses to numerous environmental factors above and below ground. Various approaches have been adopted in plant research allowing to noninvasively quantify plant growth [1]. These includeoptical methods, such as measuring one or several projections with further correlation of the area(s) to total biomass of a plant [2] or 3-D reconstruction of a plant from the images taken from different angles, spectral reflectance measurements, stationary and portable nuclear magnetic resonance imaging

The application of cavity resonators for the measurement of dielectric properties of material is well known since more than half a century . One example of this method has been shown by Bourdel *et al*, where using the TM_{010} mode of a cavity resonator, they were able to measure the complex permittivity of cigarettes and correlate it to its moisture. In our previous work on this topic, we already demonstrated the capability of microwave cavity resonators as promising tools in plant research. This method is noninvasive, fast, and integrative. It provides the opportunity to measure the plant water status and to dynamically analyze their growth by estimating total biomass of the plants. A few years ago, Sancho-Knapik *et al*. showed an easy-to-handle and nondestructive microwave technique to assess the relative water content of poplar leaves at different levels of dehydration. They demonstrated a low cost and portable device, based on a microwave digital cordless telephony path antenna that could be used under field conditions. More recently, another technique to get noninvasively leaf water status was demonstrated by Dadshani *et al*. by using a dual-mode microwave resonator. The possibility of using low-frequency microwaves not only for plants but also for the estimation of soil moisture was shown by various authors . The principle is similar in both above- and below-ground measurements: frequencies much lower than 10 GHz are chosen: 1) to obtain clear differences in relative permittivity between wet and dry substances; 2) to get sufficient penetration depth of electromagnetic waves into water; and 3) to have minor absorption due to dissolved electrolytes that are usually presented in soil and plant tissue.

In this paper, we developed a new measurement principle expanding our previous approach. As it can accommodate plants with various heights and widths, e.g., of different plant species or developmental stages, the design enables microwave resonators to be integrated in automated plan phenotyping systems. Whole plants can be transported to the resonator by dedicated mechanical carriers, and by moving the cavity in a linear motion along the vertical axis of a plant, height-dependent measurements of the dielectric properties of the plant can be consecutively gathered. Thereby, the vertical distribution of plant water content and dry mass can be computed using the changes in both resonant frequency and quality factor and supposing that absorption is mainly caused by the tissues of a plant.disadvantages in particular with respect to the inhomogeneous electric field distribution of the lowest transversal-magnetic mode TM_{010} causing an impact on the results depending on the lateral position of an object in the center of the cavity. For the measurements of plants that generally display a rather complex 3-D architecture (with stems, leaves, inflorescences, and so on), the position-dependent sensitivity of the resonator was, therefore, a drawback. To overcome this limitation and substantially reduce possible measurement errors, we redesigned a new resonator to achieve a homogeneously distributed electric field in the horizontal plane.

A. Microwave Resonator Design

The design of the resonator was developed using CST Microwave Studio simulation software (CST—Computer Simulation Technology AG, Darmstadt, Germany). Following the idea to have a homogeneously distributed electric field in the horizontal direction, we obtained conically shaped resonators (Fig. 1). Such a design allows to measure an object slice by slice by moving it vertically without any concern about its horizontal position inside the cavity, which is important for both repeatability and compatibility in automated measurement routines. To check the reliability of the simulated data, we measured the transmission parameter, S_{21}, in a wide frequency range from 1 to 2.5 GHz for resonator 1 and compared it with the simulated ones [Fig. 2(a)]. Our simulation showed harmonic oscillations of the simulated spectrum. However, the position of the resonance frequencies for the simulated and measured spectra was in good agreement, and based on these results, we could obtain the field distribution of the different modes of the resonator.

Regarding the size of the resonator, the design can be scaled up or down. Here, we constructed two resonators with different sizes for small (up to 33 cm in height and 11 cm in width) and large plants (up to 1 m in height and 36 cm in width). The corresponding measurement setups are shown in Fig. 2(b) and (c). The basic parameters and designs (3-D CAD model in SolidWorks, Dassault Systèmes S.A., France) of the cavities are given in Table I. The rings at the top and bottom sides of the resonators can be increased in height to decrease possible disturbances from outside the cavity, such as electrical noise, moving objects, and so on. For resonator 2, the ratio between height and diameter of the rings is smaller compared with resonator 1. This was done to decrease the total height of the cavity 2 in order to accommodate it inside an existing cabinet with restricted inner dimensions designed for automated plant measurement.

. (a) Vertical and (b) horizontal cross sections of the maximum electric field strength density of TM$_{010}$ mode simulated by using CST Microwave Studio. Letters in (b) show the positions inside the cavity walls at which closed-loop antennas should be preferentially placed. W denotes the position where a webcam can be installed. d_{small} is the diameter of top and bottom rings and the maximum diameter of an investigated object, and d_{large} is the inner diameter of a resonator.

To excite the electromagnetic waves and to sense them, two closed-loop antennas are used. They are connected to a Vector Network Analyzer ZVL3 or ZNC3 (Rohde & Schwarz GmbH, Cologne, Germany) via SubMiniature version A connectors. To minimize direct spurious coupling, it is important to place them at a relatively large distance from each other. Therefore, the antennas were placed at opposite sides inside the central ring at positions A and C [Fig. 1(b)]. With such an antenna position, we also sense the TM$_{110}$ mode (see Fig. 2), which when plant parts are spaced out more laterally rather than in the center can influence the measurement of the TM$_{010}$ mode. To avoid this effect, the antennas can be placed perpendicular to each other, for example, at positions A and B. The direct spurious coupling will be slightly increased, but the TM$_{110}$ mode will disappear. All results presented in this paper were done using antenna positions A and C.

B. Measured Parameters and Vertical Positioning System

The new resonator design was made to achieve a horizontally homogeneous distribution of the electromagnetic field inside the resonator. This allows to measure objects layer by layer with a resolution given by the vertical field distribution in height, i.e., Gaussian function with standard deviation, σ, equal to 4.2 and 9.5 cm for resonators 1 and 2, respectively. The obtained resonant frequencies of about 1.15 and 0.36 GHz, respectively, enable high penetration depth (more than 10 cm) of the electromagnetic field into moist tissues, allowing to sense the whole volume of a plant layer inserted into the field. Because plant tissues have larger dielectric permittivity than air, the resonance peak will be shifted to lower frequency when a plant is inside the cavity.

During each measurement, the following parameters can be acquired: the center or resonant frequency f_0, the bandwidth f (at −3 dB from the peak amplitude), and the quality factor $Q = f_0/ \ f$. Instead of the resonant frequency, one can also choose its shift relative to the frequency of the empty resonator, i.e., the change in the center frequency, CF, as a variable.

In order to measure whole plants, we implemented vertical positioning systems to either move the object through resonator 1 (Steinmeyer Mechatronik GmbH, Dresden, Germany) or resonator 2 over the object (EPOS2-50/5 motor driver and EC 45 250W motor, Maxon Motor GmbH, Germany, combined with a linear axis, item Industrietechnik GmbH, Germany). Temperature and relative humidity (RH) of the air at resonator 1 were measured by an Oak USB sensor (Toradex AG, Horw, Switzerland). A web camera (C200, Logitech International AG, Lausanne, Switzerland) was mounted at plant growth over the time of measurement. Resonator 1 is prepared mainly to monitor one single plant over time. Resonator 2 is built into an existing imaging station called Screen-House, Which allows fully automated measurements of plant.

Measurement principle of resonator 1 taken as an example. (a) Vertical displacement of the resonator with respect to a measured plant. (b) Shifting of resonant frequencies (center frequency) when a plant is introduced and moved inside the cavity in the vertical direction (z position). CF denotes the shift of resonant (center) frequency. (c) Response curve of a maize shoot (Saatmais Badischer Gelber) weighing about 0.23 g and about 25 cm in height. The shape reflects 1-D water distribution in the plant with a resolution of about 4 cm (specified by a vertical field distribution in the resonator). The integral (i.e., the area under the response curve) is correlated with the water amount in the plant.

($\varepsilon_{\text{air}} = 1$) or dried plant tissues (e.g., $\varepsilon_{\text{plant}} = 6.3$, data not shown, the highest obtained value supposing that the tissues are fully compressed after drying and have density of about 1.53-g/cm^3 This makes the method highly sensitive for water detection. Furthermore, the selected frequencies are low enough to have small absorption by water and to sense also dissolved electrolytes in plant tissue

The measurement principle of both setups is comparable and shown in Fig. 4, where resonator 1 is taken as an example. When a plant is moved through the cavity, the resonance peak shifts to lower frequencies due to the introduction of dielectric material in the electric field of the resonator . In addition, we observe a change in the quality factor of the resonance peak, which depends on the dielectric loss of the plant. Therefore, in each position of a scan, we measure spectra reflecting dielectric properties of object layers placed into the electric field. Due to the Gaussian distribution of the field along the vertical axis of the resonator, the so-called response curve of a plant can be obtained at the end of the scan [Fig. 4(c)]. In this case, the area under the curve, named Integral, contains information about the influence of each virtual slice of the plant on the resonance peak at different z positions and is related to the total water content due to the negligible influence of the dry mass of plant tissues.

D. Electric Field Verification

To verify the simulated electric field distribution inside the cavities, we used a small water-filled polyvinyl chloride (PVC) ball of 37 mm in diameter and 1-mm-thick wall. The scans of the ball placed at different horizontal positions from the center of a cavity are shown in Fig. 5 for resonator 2. This resonator constitutes the worst case of both resonators due to its large size, its construction using different materials, and the stronger impact of disturbances from outside the cavity as mentioned earlier. Nevertheless, the scans show that the sample responses are rather independent of its lateral position. In addition, we obtained a Gaussian distribution of the electric field strengt in the vertical direction with the same width, $\sigma = 9.5$ cm, as mentioned earlier. Such a distribution is caused by the open sides of our resonators and can be compared with the vertical distribution of a Gaussian beam that propagates horizontally through the resonator.

Responses obtained with resonator 2 at 15, 30, 65, 80, 100, 130, 157, and 162 mm horizontal position from the center of the cavity, with a 37-mm PVC ball filled with water, with a cylindrically shaped PVC holder (5 mm in diameter) on one side. These responses indicate that the correspond- ing electric field distributions are homogeneous in the horizontal plane and obey a Gaussian distribution along the vertical axis of the cavity.

III. EQUIVALENT CIRCUIT

In this section, we present a circuit model to illustrate from first principles the resonator's response in an intuitive fashion. We consider that the explanatory power of this model is similar to that of the cavity perturbation theory.

The equivalent circuit for the presented design of the cavity resonator can be divided into two parts. The first one is the unchangeable part, which can be described by a parallel connection of an inductance, L_0, caused by the current flow on the surface of the resonator walls, a wall resistivity, R_0, and a capacitance, C_0, of the resonator's inner side of two Integrals (10) and (15) measured for different liquids is independent of volume (see water points) and depends only on the dielectric permittivity of an MO and on both peak frequency and quality factor of the unloaded resonator. THF denotes tetrahydrofuran. Error bars reflect the composite uncertainties of two Integrals [see Fig. 6(a) and (b)], i.e., the relation between the two Integrals multiplied by the square root of the sum of their squared relative errors.

Resonant frequency temperature and humidity behavior of the empty resonator 2. The slope of dashed lines reflects the linear thermal expansion with $\alpha = 27.2 \times 10^{-6}$ K^{-1} and the temperature behavior of humid air, where the intersect with the vertical axis shows the influence of water in air. AH denotes absolute humidity.

such a shift as caused by an underestimation of the quality factor due to the influences of higher modes of the resonator (see Fig. 2).

IV. EVALUATION AND VALIDATION TESTS

A .Temperature and Humidity Dependences

We measured both unloaded resonators at various temperature and humidity values. To explain the data obtained, e.g., for resonator 2 (Fig. 8), we should take into account both the thermal expansion of Cu/Al (or of Al in the case of resonator 1) and the temperature dependence of humid air with a defined relative permittivity. The water content of the air would decrease the resonant frequency due to its higher dielectric constant. To calculate the relative permittivity of the air–water mixture. In our case, the best model to describe this air–water mixture is the Landau and Lifshitz, Looyenga mixture model. After fitting the data, of Integral (8) of resonator 1 on volume of water in glass tubes with different diameters (0.26, 0.6, 0.84, and 1.11 cm) and in wet office paper (70-g/m^2 grammage), which has respective values of "number of sheets" to width (cm) to length (cm): 1 × 1 × 2.5, 1 × 1 × 5, 1 × 4 × 5, 1 × 2 × 10, 1 × 4 × 10, and 5 × 4 × 10 (from left to right points on the plot). Volume for dry paper dependence is a volume of dry paper taking into account the sheet thickness of 0.01 cm. Filled color of points reflects the relation between length and diameter-related size of the measured samples. Influence of sample borders schematically shown on the right side, where E_n and E_t are the descriptions of the electric field in terms of normal and tangential (related to sample borders) directions, respectively. The height of scans was 30 cm.

we obtained a coefficient of linear thermal expansion, α, of the resonator equal to $27.2 \times 10^{-6}\ \mathrm{K}^{-1}$, which is sufficiently close to that of Al ($24 \times 10^{-6}\ \mathrm{K}^{-1}$). As we can see, water in air can lead to shifts of the resonant frequency of more than 50 kHz (with

resonator 1, this shift is at least two times higher), which needs to be considered in experiments by measuring both temperature and humidity of the air close to the resonator and temperature of the resonator itself. Another way to avoid an influence of temperature and humidity is to measure the unloaded resonator (f_0 and Q_0) between runs with an MO to compensate for the impact of this factors in calculations of MO's Integrals using (8) or (10) and (15). In both cases, temperature dependence of the MO's dielectric constant should also be taken into account.

B. Effects of Sharp Borders and Influence of the Height of a Water Column

column will drop by $\varepsilon^{\pm}_{\text{water}}$ times. This leads to a change of the

field distribution around as well as inside the sample. Due to this decrease, the field inside C_{MO} becomes smaller in either (7a) or (9), leading to a reduction of the related Integral. This effect depends directly on the side-to-top/bottom corners of the sample. We found that it correlates with the $(d_{\text{MO}}/L_{\text{MO}})^{1/2}$ ratio.

C. Noise Level and Accuracy

The noise level in Fig. 9 is calculated as an error of the estimated resonant frequency multiplied by the total length of a scan (noise level = 0.01 MHz × 300 mm). In the case of a scan over the complete height (see Table I), this value is 3.3 MHz mm for resonator 1 and about 0.01 MHz ×

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respectively, with an accuracy of <10%. The accuracy can be improved more than ten times by measuring with higher number of steps and subsequent smoothing the height dependence taking into account that the second derivative should not exceed that of a Gaussian function with respective σ (see Section II-B). In addition, the height of each scan can be decreased up to three times [until reaching the electric field

During the measurement of water columns of different volumes [see Fig. 6 (insets)], we observed small deviations of the Integrals from a linear dependence on water volume with decreasing height of the water column. To investigate this effect, we prepared an additional experiment using different water-filled glass tubes with inner diameters, d_{MO}, of 0.26, 0.6, 0.84, and 1.11 cm [Fig. 9 (closed dots)]. We found almost no effect when the height of samples, L_{MO}, became larger than $10d_{\text{MO}}$. In the case of a plant, d_{MO} is related to the thickness either of the leaves or the stem. This means that the relation $L_{\text{MO}} > 10d_{\text{MO}}$ holds automatically in most cases, because the thickness of leaves usually is not higher than a few millimeters, while their length is usually bigger than ameters, and even for a thick stem, its length is much bigger than its diameter. To explain this dependence at lengths smaller than $10d_{\text{MO}}$, one can use simple diagrams as shown at the right side of Fig. 9. Here, the vertical alignment of the electric field inside the resonator plays an important role. A parallel oriented (tangential) field, E_t, at the side of a sample will not be changed inside the sample, but a perpendicular (normal) field, E_n, at the sharp top/bottom borders of a waterly two: paper and water. The model and measured integrals (see Fig. 9) allowed to obtain the following

papers' parameters: true density of $0.9 \pm 0.3\ \mathrm{kg/m^3}$, dielectric constant of 2.5 ± 0.8 (1150 MHz, ~27 °C), and porosity of 18% ± 4%. The volumetric moisture for the wet paper here is about 55%, which is relatively small in comparison with well-watered plants. Therefore, for plants, Integral values should be even closer to free water values, which allow to conclude that the Integral accurately reflects the water amount in tissues.

1000 mm = 10 MHz mm for resonator 2. Taking into account the noise level, we can estimate volumes larger thant should be noted that for the calculations, water was considered to be free, which can be proved taking into account the mean porous size of paper to be 10 μm. This results in hundreds of water layers even at 4% moisture. To obtain paper parameters more precisely, one should use higher masses of paper. However, the main aim of this exper- iment was to show the working procedure for small samples and to find the limits when the method still yields acceptable results.

E. Measurements of Plants

Each measurement consists of a scan of an MO in the vertical direction. As stated in Section IV-D, we can obtain precise results for the samples of finite length and

strength height (see Table I)] for both resonators depending on the height of an MO. This results in a smaller noise level.

D. Water in Tissue

Additional to glass tubes, we tested dry and wet pieces of bond paper (Baier & Schneider GmbH, Heilbronn, Germany) with a weight of 70 g/m^2, a thickness of about 0.1 mm, and with different lengths and widths. The results are shown in Fig. 9 as black bordered squares and triangles, filled with the color that reflects the $L_{\mathrm{MO}}/d_{\mathrm{MO}}$ relation to be sure that sharp border effects (see Section IV-B) are negligible. Such a test allows getting an impression of how sensitive the method can be and which aspects are important for future plant investigations. Measurements of dry paper (triangles) reflect its dielectric constant, density, and porosity. In addition, dry bond paper consists of 4%–4.5% of water at RH = 30% and $T = 26$ °C, which should be taken into account as well. Wet paper (squares) was prepared by placing dry paper into water completely, which allows to reach a paper moisture of 61% ± 5% by mass. The most proper results were obtained by using again the Landau and Lifshitz, Looyenga mixture model. For dry paper, we used a mixture of three components: paper, air, and water (4%), and for the wet edge of the pot to avoid errors caused by the influence of moisture in pots. Additional calculations are required to take this into account and to estimate the water content in the pots. A plant cannot be measured completely due to several reasons. For resonator 1, even a relatively small pot of 9 cm in diameter is relatively big in comparison with the bottom/top rings of the resonator (d_{small} in Table I). This issue leads to a large attenuation and the resonance peak cannot be found anymore. For resonator 2, the setup cannot completely reach the plant tissues located close to the surface of the soil due to limitations in the size of pots (about 18 cm height) that can be used in the described imaging setup, where the resonator is placed.

A typical measurement procedure for a maize plant. The eight days old plant (Saatmais Badischer Gelber) of about 1.9-g fresh weight (FW) and about 15 cm in height with leaves bending down was measured down to the point when the pot ($7 \times 7 \times 18$ cm^3) filled with peat soil (Einheitserde Typ ED73, Einheitserde- und Humuswerke Gebr. Patzer, Germany) started to get inside the resonator when the signal became no longer detectable (black solid line at position 300 mm). After harvesting the plant, the pot was measured again down to the same point (red dotted line), and the position, when the pot started to influence the measurement, is indicated by the blue dashed line. The difference between the two curves yielded the response of the plant (dark green dashed-dotted line) which did not going back to zero, indicating that the plant was not completely measured. By knowing the distribution of the field inside the resonator, it is possible to fit the missing part of the response, called "Gaussian tail," which, together with the measured part, gives the full plant response. The area under the response linearly correlates with the water amount of the plant [see (8)].ach leads to a nonlinear dependence of the Integral on the water amount especially for small plants, because the plant tissue just above the ground level cannot be measured completely. In addition, in this case, it is important to measure the calibration curves for each plant genotype due to its different heights and widths.

It should be noted that for different measurement procedures, one should know the exact position of the pot. The best method is to measure a reference pot filled with soil but without a plant. This can help especially when different plant species are measured and only one calibra- tion curve is used. After the measurements of each plant, we fit the end of each response using both the measured reference pot and the "Gaussian tail." The response from reference pot should be multiplied by variable amplitude due to unknown water amount in measured pot with a plant (supposing that it has the same law of soil water distribu- tion). In this case, we will obtain the total response curve without pot numerically, which allows us to use a general calibration curve.

F. Responses of Plant Layers and Deconvolution

In order to show this, we measured two leaves of a maize plant (genotype B73, about two months old) at different developmental stages, where the first leaf (Leaf 2) was smaller and drier in comparison with the second one (Leaf 5). Each leaf was scanned twice within 5 min, yielding four nearly identical responses (two by moving the cavity down and two backward). The standard deviation was determined to be smaller than 0.013 MHz for each scanning position. After the measurements with resonator 2, we cut the leaves into 5-cm-long segments and weighed them to get the respective FW. The segments were then put into an oven at 60 °C for several weeks to obtain the dry weight (DW), and the water amount (WA = FW − DW) at the day of harvest was calculated. To obtain the calculated responses shown in as blue dots, green dashed-dotted lines, orange dashed lines, and red solid lines, we convoluted a normalized unit response, i.e., a Gaussian distribution with $\sigma = 9.5$ cm (Fig. 5), with the dis- tribution of WA, FW, DW, and mixed model volume (MMV), respectively. The MMV was calculated as an FW$\times(\varepsilon_r - 1)$, where ε_r is the dielectric constant for mixture of water and maize dried tissue using the Landau and Lifshitz, Looyenga mixture model . The calculated ε_r of segments varied from 7.8 (almost completely dried tip) to 67.6 and from 45.1 to 66.2 for Leaf 2 and Leaf 5, respectively. In addition, the respective responses were multiplied by coefficients to fit the measured responses (black solid curves in Fig. 11). The good correlations of the measured data with the convo- luted results (Fig. 11) indicate that the method works well with plant tissues and that the theory presented here provides a good description of the resonators and the measurement principle. Moreover, applying fitting procedures or deconvolution to measured responses can improve the resolution of measured 1-D water profiles of plants.

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V. CONCLUSION

We designed dedicated microwave cavity resonators that are suitable for measurements of water amount and water distribution in plant tissues. The resonators have been characterized and thoroughly tested for future use in the laboratory and in a greenhouse with an automated setup for routine plant growth measurements. The homogeneously distributed electric field in the horizontal plane of the resonator cavities allows to noninvasively measure the 1-D water distribution in a plant independent of its position inside the resonator.

All this demonstrates a good linear dependence of the shift of resonant frequency on both the real part of relative permittivity and the volume of an investigated object. When changes in quality factor, temperature, and RH are also taken into account, the resonators allow to precisely measure the dielectric properties of differently shaped objects by knowing only their volumes. Taking into account the small losses of water at working frequencies mentioned in this paper. This makes the method applicable to nondestructive monitoring and quantifying total biomass of plants developing over time.

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