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RESEARCH ARTICLE

A New MM-Wave Backscattering Method for Estimating Water Content in Leaves To Minimize Demand on Water Resources

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ABSTRACT This paper is the first to propose a non-destructive measurement method based on reflection of mm-wave electromagnetic waves from leaves to continuously monitor water content in leaves. We propose to use backscattering, i.e., sending a sweeping sinusoidal signal toward a leaf and measuring the backscattered reflection to estimate water content in a leaf. This method allows for a hand-held device or a drone to perform measurements in the field. The proposed method is agnostic to the type of leaf observed and does not prescribe a required distance from which measurements are taken. Given appropriate transmit power and a suited narrow-beam antenna, this method can be applied at a wide range of distances. The results show that this approach allows for tracking water content in a leaf over time capturing fine grain details, can predict when water is added to the pot, tracks how the plant consumes water over time, and shows the optimal points in time to add more water.

INDEX TERMS Backscattering, engineering for biology, inference from mm-wave propagation, measurement methodology.

I. INTRODUCTION

The agricultural sector uses over 70 % of the world's annual water consumption [1], and it will be one of the first to feel the strain as demand supersedes available resources. One of the ways to make modern agriculture more efficient, both in using watering resources as well as growing healthier crops, is to accurately predict when crops need to be watered and with which amount of water. One possible approach to do this is to monitor hydration levels of leaves in the field, without disturbing them.

Determination of the water content in leaves has been of high interest in numerous aspects of botany science including basic research and various fields of applied biology [2]. However, none of them are designed for continuous monitoring of plants in the field.

Different measurement techniques have been developed for monitoring individual plants and can be classified into destructive methods such as resistance measurements in plants [3], [4] or thermo-gravimetrical quantification of hydration levels [5], [6], [7], and non-destructive methods such as terahertz radiation [8], [9], [10] and spectroscopy [11], [12], [13]. However, none of them have been focused on continuous monitoring of water content in leaves to determine the optimal time for watering plants as well as the amount of water needed for successful growth of the crop.

This paper is the first to propose a non-destructive measurement method based on reflection of electromagnetic waves at mm-wave frequencies to determine how water content in leaves changes over time. Note that many of the measurement techniques developed for measuring water content in leaves are focused on very low frequencies (e.g., < 1 GHz) where electric conduction is easy to measure but requires the leaf to be destroyed in the process [3], [4] or very

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high frequencies (e.g., > 100 GHz) where imaging resolution allows for observing detailed changes in leaves over time but is expensive and hard to deploy in the field [14]. More importantly, none of these methods allow for continuous monitoring of plants in the field to determine when more watering is needed.

To address this problem, we propose a method for measuring water content in leaves at mm-wave frequencies. We choose this frequency band because bound water molecules play a major role at these frequencies allowing for easy tracking of hydration conduction, temperature changes, hydration levels changing, etc. [15]. Since water content or water resistance in leaves cannot be measured directly without destroying or damaging a plant, we propose a non-destructive methodology using backscattering, i.e., sending a sweeping sinusoidal signal toward a leaf and measuring the backscattered reflections to estimate losses due to water content in a leaf. This method allows for designing hand-held devices similar to a RFID scanner that could test for water content changes in leaves. Similarly, such a device could be put on a drone or multiple drones to perform testing in a field. The proposed method does not prescribe a distance from which measurements are collected because we remove the impact of losses in the measurement environment by subtracting the reflected signal from a metal plate at the same distance from the overall measured signal.

Furthermore, we remove the impact of leaf dry matter by subtracting the reflected signal from a dry leaf from overall measurements. That way, we ensure that only water content changes are observed in a leaf. Our results show that this approach allows for tracking water content in a leaf over time, can predict when water is added to the pot, tracks how the plant consumes water over time, how water levels change hourly, and shows what the optimal points in time to add more water are.

This new research direction in water sustainability opens doors to research in mm-wave electronics specifically designed to be compact, low-cost, lightweight, and very directional so they can be mounted on drones. Furthermore, it allows biologists to study plant physiology in-depth and explain some processes within the plants that were not possible to observe before. Finally, it gives strong motivation for autonomous vehicles and AI to coordinate monitoring of large fields of crops over long periods of time.

The remainder of the paper is organized as follows. Section II describes a newly proposed method for estimating water content in plants, Section III presents measurement setup and results collected from 4 different plants, and Section IV concludes the paper.

II. A NEW MM-WAVE BACKSCATTERING METHOD FOR ESTIMATING WATER CONTENT IN PLANTS

Water evaporation in a leaf is often modeled as a water vapor resistance in a leaf [16]. The model assumes two sets of resistance, one on the surface of the leaf and the other one on the bottom of the leaf. They are assumed to be connected in parallel [16]. Each resistance consists of resistance due to inter-cellular air space (ias), due to stomata (st), due to boundary layer of air (bl), and due to cuticle (c), and they are connected as illustrated in Figure 1.

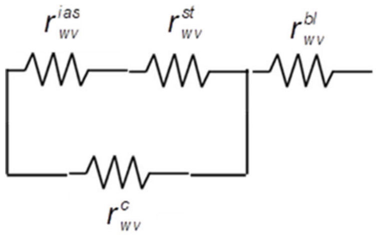

FIGURE 1. **Model of the surface leaf resistance [16].**

The resistance model in [16] shows that different parts of the leaf can be modeled as a resistance network. Both the top and bottom of the leaf have the same resistance network structure connected in parallel to model the full leaf. This model was only an inspiration for our work indicating that the leaf can be treated as a circuit. In the introduction, we have cited several papers that used resistance of a leaf to estimate water content. However, this model (and cited papers) is appropriate only at lower frequencies where the impact of conductance and capacitance of the leaf can be neglected. In contrast, we propose a propagation model through the leaf that is applicable at mm-wave frequencies. In particular, we propose a modified radar backscattering model, where radar cross-section is modified to include losses due to water content changes in the leaf. The assumption is that when water is present in the leaf, the leaf is more resistant than when there is no water present (dry leaf) [3], [4], [16].

The difficulty of measuring resistance approach is that in order to measure water vapor of a leaf, the leaf has to be damaged. To address this issue, we propose a non-destructive method that allows for indirect measurements of overall water content in a leaf.

To estimate levels of hydration in a leaf, we propose to measure the reflection coefficient $|S_{11}|$ using a network analyzer that can operate in the 21 GHz to 40 GHz frequency range. We collect $|S_{11}|$ in a wide frequency range to allow for finer-grain resolution of observations. Reflection coefficient $|S_{11}|$ can be calculated as

$$|S_{11}| = \sqrt{\frac{P_r}{P_t}}, \tag{1}$$

where P_r is the received power of the backscattered wave and P_t is the transmit power. The received power after backscattering can be calculated using a modified radar equation [17], i.e.,

$$P_r = \frac{P_t G^2}{(4\pi)^2 R^4} \frac{\lambda^2}{4\pi} \sigma_s L_{\text{setup}}, \tag{2}$$

where P_r, P_t, and G, are the monostatic backscattered received power, the transmit power, and the gain of the antenna, respectively. Parameter R denotes the distance between the antenna and the object of reflection, λ denotes the wavelength of measurements, and L_{setup} captures losses of the measurement setup, such as antenna impedance mismatch, polarization mismatch, etc. Parameter σ_{s} is the radar cross section of the reflecting object. The radar cross section of a two-ray propagation model can be written as

$$\sigma_{\text{s}} = \frac{4\pi}{\lambda^2} S^2 \left|\Gamma_{\text{s}}\right|^2 \left(1 + e^{-2Ld}\right), \tag{3}$$

where S is the area of reflection. $|\Gamma_{\text{s}}|$ is the reflection coefficient from the leaf surface and $|\Gamma_{\text{s}}|\, e^{-2Ld}$ is the reflection coefficient after a wave has traveled through a leaf and reflected back to the antenna. The parameters L and d denote propagation losses through a leaf and the leaf thickness, respectively.

Since we are focused on estimating losses L due to the presence of water in a leaf, we need to eliminate all other unknown values from equation (2) and losses due to dry matter in the leaf. One way to do that is to reflect a signal off a metal surface in which case $|\Gamma_{\text{s}}| \approx 1$ and to measure dry leaf losses L_{d}. When a metal plate is present, equation (2) simplifies to

$$\left|S_{11,\text{metal}}\right| = \sqrt{\frac{G^2\lambda^2}{(4\pi)^3 R^4} \frac{4\pi}{\lambda^2} S^2 L_{\text{setup}}}, \tag{4}$$

Due to the leaf and reference metal sheet having roughly the same area, we can normalize $|S_{11,\text{leaf}}|$ from (1) by $|S_{11,\text{metal}}|$ from (4), canceling out L_{setup}, the gain of antennas, and distance from the leaf and obtaining an expression that can be solved for L, which contains the loss due to water presence in the leaf. This normalization can be done for any distance, provided that the transmit power is large enough and the antenna beam stays focused on the leaf and reaches the metal plate and/or leaf. This means that by measuring the reflected signal from a metal plate with a similar area as a leaf, under the same incident angle, we can estimate all parameters needed for measuring the reflection coefficient from a leaf. Thus, the loss L accumulated due to propagation through a leaf can be calculated as

$$L = -\ln \frac{\frac{|S_{11}|^2}{\left|S_{11,\text{metal}}\right|^2 |\Gamma_{\text{s}}|^2} - 1}{2d}, \tag{5}$$

and loss L_{d} can be calculated as

$$L_{\text{d}} = -\ln \frac{\frac{\left|S_{11,\text{dry}}\right|^2}{\left|S_{11,\text{metal}}\right|^2 |\Gamma_{\text{s}}|^2} - 1}{2d}, \tag{6}$$

The reflection coefficient when a leaf is present can be calculated using discontinuity equation, i.e.,

$$|\Gamma_{\text{s}}| = \left|\frac{Z - Z_0}{Z + Z_0}\right|, \tag{7}$$

where,

$$Z = \frac{d}{w}\sqrt{\frac{\mu}{\epsilon}} \tag{8}$$

is the characteristic impedance of a leaf, and d is the leaf thickness, w is the average width of the antenna beam illuminating the leaf according to the data sheet, and μ, ϵ describe the magnetic and electric properties of the leaf [18], and

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 377\Omega \tag{9}$$

is the characteristic impedance of air, where μ_0, ϵ_0 describe the magnetic and electric properties of the air.

The losses due to water content changes can be tracked as

$$\Delta L = \text{movmin}(L - L_{\text{d}}). \tag{10}$$

In the far field, equation (1) is the definition of the monostatic backscattered signal and holds regardless of the frequencies. Equation (5) was derived from the definition of S_{11} (1), the radar equation (2), and the two-ray propagation model for radar cross-section (3). To derive (5), it is only necessary to assume that the far field condition holds and that the metal sheet has roughly the same area as the leaves examined. Both conditions are fulfilled in our setup. The losses due to propagation through the leaf are due to the resistance of the leaf, which is impacted by the water content. In a dry leaf, no water is present, and the leaf has a lower resistance than when there is water present [3], [4], [16]. By subtracting the losses through a dry leaf from the measured overall loss, we ensure that we only track the losses associated with the water content. This resistive approach is sufficient because we are measuring backscattered line-of-sight signals that are best described by the radar equation (2) whereas more complex channel modeling options are more appropriate for wireless communication where multiple reflections off objects between the antennas are expected.

III. EVALUATION OF NEW BACKSCATTERING METHOD

A. DESCRIPTION OF MEASUREMENT SETUP

Figure 2 shows the measurement setup used to collect the data presented in this paper. It shows the network analyzer (Agilent PNA N5224A) which is capable of collecting S-parameters in the frequency range of interest (i.e., 21 GHz to 40 GHz) and two horn antennas with a typical gain of 10 dBi and 40 degrees beamwidth [19]. Figure 2 (a) shows the setup with the metal plate, Figure 2 (b) shows the setup when the leaf is present, and Figure 2 (c) shows a diagram of the setup. The leaf was held in place using clamps, ensuring the leaf was unable to move with respect to the antenna. The experiments were performed in an air-conditioned laboratory. Therefore, variations in temperature and humidity are negligible. The frequency range is 21 GHz to 40 GHz, the VNA was set to a frequency sweep with 2001 points. At each frequency point, we calculate dry losses according to (6) and measured loss according to (5). For every measurement in time, the difference of measured and dry loss is averaged over the entire frequency band. This average loss is then plotted over time according to (10).

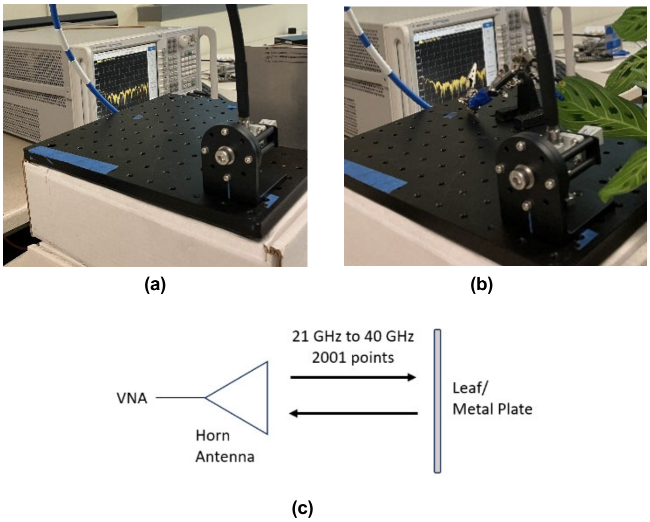

FIGURE 2. Measurement setup for backscattering with the metal plate (a), live plant (b), and schematic representation (c).

B. RESULTS AND FINDINGS

This section shows results that illustrate how the proposed method can be used to track hydration processes in plants. To illustrate our findings, we analyze four different types of plants – those with thick narrow leaves (Gold – Sansevieria trifasciata 'Gold Flame') [20], thick wide leaves (Lemon – Maranta leuconeura) [21], thin wide leaves (Silvia – Calathea roseopicta) [22], and thin narrow leaves (Money – Pachira aquatica) [23]. All four plants are selected to represent different types of plants based on hydration needs and leaf properties. The Gold Flame plant has low to medium water demand, the Lemon plant has medium water demand, and the Silvia and Money plants have medium to high water demand. With these four plants, we cover water demands from low to high and a range of leaf shapes from very long, narrow and thick to big, wide, thin leaves. The objective was to monitor live leaves and their hydration processes over time. In the mm-wave range, there are no comparable methods that we could consider. Classic botanical methods often involve the destruction of the leaf, and lower frequency approaches have limited comparability with our high-frequency approach. Simultaneously measuring soil moisture is possible but would not provide insight on the water content in the plant leaves. Drying of the soil over time need not necessarily translate to the plant consuming that water, which is what makes the proposed method valuable. Please note that such measurements/data is not available in the literature, because plants need to be damaged to collect that information (by either probing or cooking them at very high frequencies). For every plant type, one specimen was tested.

We have collected the data using the setup described in Section III-A by recording propagation through leaves every 30 minutes over 7 days and calculating losses due to water content change as a function of time. We left all four plants without hydration for 7 days and added one cup of water at the beginning of the measurement cycle. Figure 3 shows pictures of the four plants used in the experiments and Figure 4 shows our findings.

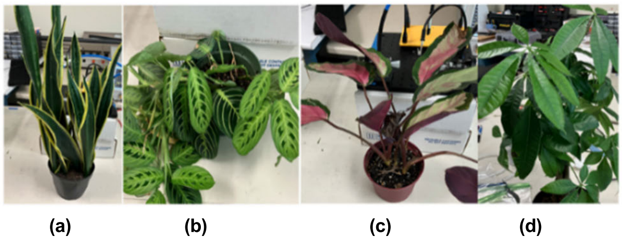

FIGURE 3. Photo of the plants: Gold flame (a), Lemon (b), Silvia (c), and Money (d).

Gold flame has thick narrow leaves and based on the description *needs hydration once in two weeks*. Originally from West Africa, the plant prefers part shade and is evergreen with long, stemless leaves that are a deep green with yellow stripes lining the edges. It is a popular low-maintenance houseplant that usually reaches a height of up to 60 cm when kept indoors. The dimensions of the measured leaf are 340 mm from the tip to the base, with a width of 48 mm at the widest part. The measured thickness is 3.1 mm. We can observe from Figure 4 (a) that the water content has increased at the beginning of the measurements indicating change in hydration levels due to watering performed at that time. Furthermore, we can observe rapid changes in propagation loss for the first 48 hours. Then the hydration levels start oscillating for the next 2-3 days. After that, hydration levels continue dropping indicating that after 160 hours (about 7 days), the plant should be watered again. This process continues until a new hydration cycle is repeated when we can observe a new jump in hydration levels. This is sooner than recommended by the plant maintenance description.

Lemon plants have thick wide leaves and based on the description *needs hydration every one to two weeks*, ensuring moist soil. It is also called prayer plant, due to the characteristic motion of leaves upwards during night. The tropical plant is evergreen and has elliptic leaves with veins emerging from the central stem in a fishbone pattern. The color is light green to yellow around the stem, with dark green spots between veins. The dimensions of the measured leaf are 95 mm from the tip to the base, with a width of 48 mm at the widest part. The measured thickness is 0.4 mm. From Figure 4 (b), we can observe that at the beginning of the measurements, losses due to water content increase as expected. Furthermore, we can observe large fluctuations in water content in a leaf during day and night cycles. This process stops after about 140 hours and the losses due to water content in a leaf start dropping significantly. This indicates the optimal time to water the plant again is after 5-7 days, which is in agreement with the recommendations.

Silvia plant has thin wide leaves and based on the description *needs hydration every couple of days* to ensure that the soil is always moist. This tropical evergreen plant from

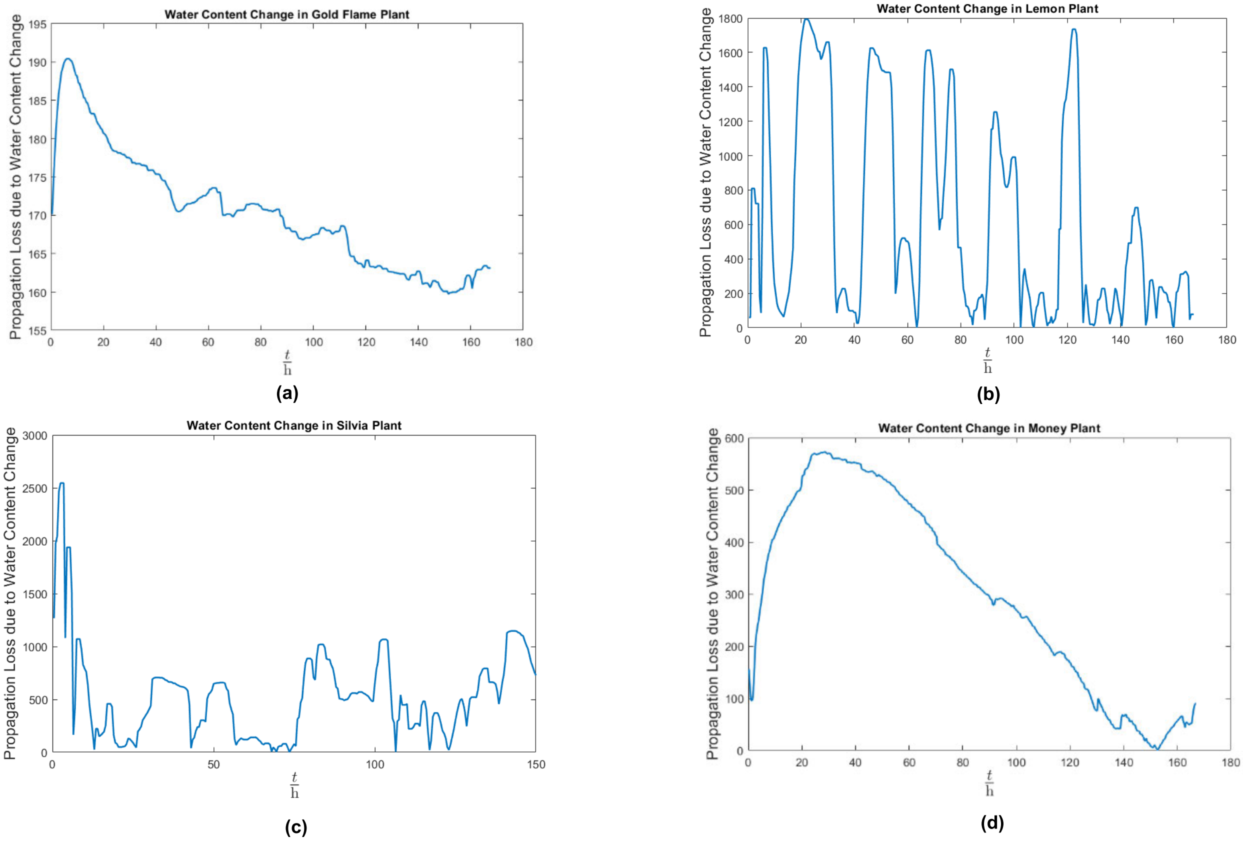

FIGURE 4. Average propagation loss due to water content change as a function of time in Gold flame leaf (a), Lemon leaf (b), Silvia leaf (c), and Money leaf (d).

South America is also referred to as Goeppertia roseopicta. It features big leaves in the shape of an ellipse, that are dark green around the edges and light green in the center, with red/pink overlays. It is most commonly kept indoors for decorative purposes and typically reaches a height of up to 40 cm. The dimensions of the measured leaf are 165 mm from the tip to the base, with a width of 113 mm at the widest part. The measured thickness is 0.4 mm. From Figure 4 (c), we can observe that the leaf has an increase in hydration after watering, then has a large dynamic range in propagation loss due to hydration during the first two days, and then starts redistributing water content across the leaf registered on the plot as an increase in hydration content. Then the water content drops and the plant struggles to retain water content in the leaf. By day 5, this process has concluded, and the leaf starts losing hydration levels indicating optimal time to water the plant is between 4 and 7 days as suggested by the recommendations.

Money plant has thin narrow leaves and based on the description *needs hydration every one to two weeks* ensuring medium to wet soils. Also known as water chestnut, it naturally grows in rainforests in Mexico and South America. Indoors, it is often kept as a bonsai, with a wooden braided trunk. The plant is evergreen with bright green leaves in the shape of a highly eccentric ellipse with a sharp tip. The dimensions of the measured leaf are 135 mm from the tip to the base, with a width of 45 mm at the widest part. The measured thickness is 0.5 mm. From Figure 4 (d), we can observe that the leaf has an increase in hydration after watering, achieves optimal water distribution after 2-3 days, and then starts struggling to retain hydration levels. This indicates that optimal hydration time might be after 3 not 7 days.

Comparing the plots, we observe that the Gold Flame plant and Money plant in Figure 4 (a) and (d) have similar levels in propagation loss and exhibit a similar shape over time. Conversely, we see that the Lemon plant and Silvia plant in Figure 4 (b) and (c) exhibit larger levels of propagation loss and a higher dynamic range that illustrates a day/night rhythm. This suggests that these two plants with thinner and bigger leaves are more actively distributing water among leaves compared to the Gold Flame and Money plant.

IV. CONCLUSION

The findings in this paper illustrate the importance of tracking water content in plants, both for the health of the plants and for saving water as a precious resource on this planet. This work shows that it is possible to continuously monitor plants in the field undisturbed for better understanding of plant physiology. Our method would also work on plants with different types of leaves than examined in this paper. The very thin, non-conductive layer of wax on some leaves would insignificantly impact wave propagation, so our method still works. For leaves with serrations, the beam can be focused on the center of the leaf so that serrations do not have any impact. Our method can even be applied to plants such as cacti, that do not have leaves but instead store water in their stems, on which we can apply our method.

A drawback is the necessity for reference measurements both for reflection off a metal plate as well as reflection off a dry leaf. However, these measurements are needed only once. Future work includes designing a system based on a handheld device or mounted on a drone that can be tested in the field.

REFERENCES

[1] P. H. Gleick, *The World's Water*, vol. 7. Washington, DC, USA: Island Press Center Resource Economics, 2011, doi: 10.1007/978-1-59726-228-6.

[2] L. A. Spomer, "Techniques for measuring plant water," *HortScience*, vol. 20, no. 6, pp. 1021–1028, Dec. 1985, doi: 10.21273/hortsci.20.6.1021.

[3] M. I. N. Zhang and J. H. M. Willison, "Electrical impedance analysis in plant Tissues8," *J. Experim. Botany*, vol. 44, no. 8, pp. 1369–1375, 1993, doi: 10.1093/jxb/44.8.1369.

[4] L. Ríos-Rojas, F. Tapia, and L. A. Gurovich, "Electrophysiological assessment of water stress in fruit-bearing woody plants," *J. Plant Physiol.*, vol. 171, no. 10, pp. 799–806, Jun. 2014, doi: 10.1016/j.jplph.2014.02.005.

[5] H. Barrs and P. Weatherley, "A re-examination of the relative turgidity technique for estimating water deficits in leaves," *Austral. J. Biol. Sci.*, vol. 15, no. 3, p. 413, 1962, doi: 10.1071/bi9620413.

[6] R. E. Smart and G. E. Bingham, "Rapid estimates of relative water content," *Plant Physiol.*, vol. 53, no. 2, pp. 258–260, Feb. 1, 1974.

[7] S. K. Arndt, A. Irawan, and G. J. Sanders, "Apoplastic water fraction and rehydration techniques introduce significant errors in measurements of relative water content and osmotic potential in plant leaves," *Physiologia Plantarum*, vol. 155, no. 4, pp. 355–368, Sep. 23, 2015, doi: 10.1111/ppl.12380.

[8] S. Hadjiloucas, L. S. Karatzas, and J. W. Bowen, "Measurements of leaf water content using terahertz radiation," *IEEE Trans. Microw. Theory Techn.*, vol. 47, no. 2, pp. 142–149, Feb. 1999, doi: 10.1109/22.744288.

[9] B. Breitenstein, M. Scheller, M. K. Shakfa, T. Kinder, T. Müller-Wirts, M. Koch, and D. Selmar, "Introducing terahertz technology into plant biology: A novel method to monitor changes in leaf water status," *J. Appl. Botany Food Qual.*, vol. 84, pp. 158–161, 2011. [Online]. Available: https://api.semanticscholar.org/CorpusID:55248739

[10] R. Gente and M. Koch, "Monitoring leaf water content with THz and sub-THz waves," *Plant Methods*, vol. 11, no. 1, p. 15, 2015, doi: 10.1186/s13007-015-0057-7.

[11] T. Cheng, B. Rivard, and A. Sánchez-Azofeifa, "Spectroscopic determination of leaf water content using continuous wavelet analysis," *Remote Sens. Environ.*, vol. 115, no. 2, pp. 659–670, Feb. 15, 2011, doi: 10.1016/j.rse.2010.11.001.

[12] J. R. Rodríguez-Pérez, C. Ordóñez, A. B. González-Fernández, E. Sanz-Ablanedo, J. B. Valenciano, and V. Marcelo, "Leaf water content estimation by functional linear regression of field spectroscopy data," *Biosyst. Eng.*, vol. 165, pp. 36–46, Jan. 2018, doi: 10.1016/j.biosystemseng.2017.08.017.

[13] A. F. H. Goetz and J. W. Boardman, "Spectroscopic measurement of leaf water status," in *Proc. Int. Geosci. Remote Sens. Symp.*, vol. 2, 1995, pp. 978–980, doi: 10.1109/IGARSS.1995.521114.

[14] R. Gente, A. Rehn, T. Probst, E.-M. Stübling, E. C. Camus, A. A. Covarrubias, J. C. Balzer, and M. Koch, "Outdoor measurements of leaf water content using THz quasi time-domain spectroscopy," *J. Infr., Millim., Terahertz Waves*, vol. 39, no. 10, pp. 943–948, Jul. 17, 2018, doi: 10.1007/s10762-018-0520-4.

[15] V. Komarov, S. Wang, and J. Tang, "Permittivity and measurements," in *Encyclopedia of RF and Microwave Engineering*. Hoboken, NJ, USA: Wiley, Apr. 15, 2005, doi: 10.1002/0471654507.eme308.

[16] P. S. Nobel, *Physicochemical and Environmental Plant Physiology*. Amsterdam, The Netherlands: Elsevier, 2020, doi: 10.1016/c2018-0-04662-9.

[17] S. W. Henriksen, "Radar-range equation," *Proc. IEEE*, vol. 63, no. 5, pp. 813–814, May 1975, doi: 10.1109/proc.1975.9829.

[18] C. Matzler, "Microwave (1-100 GHz) dielectric model of leaves," *IEEE Trans. Geosci. Remote Sens.*, vol. 32, no. 4, pp. 947–949, Jul. 1994, doi: 10.1109/36.298024.

[19] LB-28-10 26.5-40.0GHz Standard Gain Horn Antenna. Accessed: Mar. 11, 2024. [Online]. Available: https://www.ainfoinc.com/antenna-products/horn-antennas/standard-gain-horn-antennas/lb-28-10-64-c-2-4f-frequency-extended-standard-gain-horn-antenna-22-5-45ghz-10db-gain-2-4mm-female

[20] *Sansevieria Trifasciata 'Gold Flame'—Plant Finder*. Accessed: Apr. 15, 2023. [Online]. Available: https://www.missouribotanicalgarden.org/PlantFinder/PlantFinderDetails.aspx?taxonid=442909&isprofile=0&

[21] *Maranta Leuconeura—Plant Finder*. Accessed: Apr. 15, 2023. [Online]. Available: https://www.missouribotanicalgarden.org/PlantFinder/PlantFinderDetails.aspx?kempercode=b604

[22] *Calathea Roseopicta—Smartgarden Guide*. Accessed: Apr. 15, 2023. [Online]. Available: https://smartgardenguide.com/calathea-roseopicta-care/

[23] *Pachira Aquatica—Wikipedia*. Accessed: Apr. 15, 2023. [Online]. Available: https://en.wikipedia.org/wiki/Pachira_aquatica

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