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Outdoor Measurements of Leaf Water Content Using THz Quasi Time-Domain Spectroscopy

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Abstract We report the first outdoor measurements for continuous in vivo leaf-water monitoring using THz spectroscopy. For this, we have developed a compact and portable THz quasi time-domain spectrometer which can be powered by a battery. We monitor the water status of a corn plant (*Zea mays*) and discuss the influence of the day-night variations of the outdoor temperature.

Keywords THz · QTDS · Leaf water

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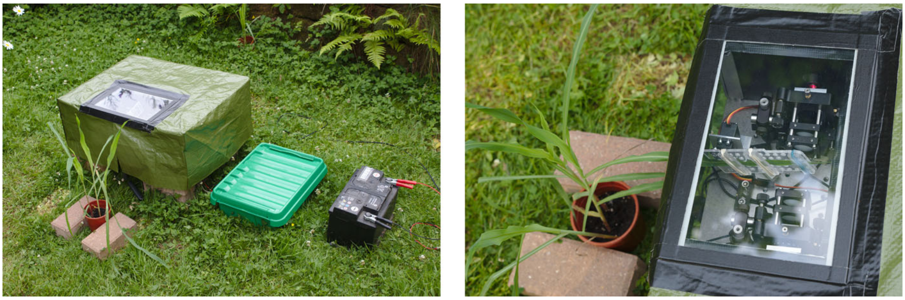
Since terahertz (THz) waves are quite heavily absorbed by water THz spectroscopy is well suited to study the water status of plants. This fact has been known for more than 20 years and several demonstrations have already been performed, predominantly using THz time-domain spectroscopy [1–6]. Yet, a cost-effective alternative is THz quasi time-domain spectroscopy (QTDS). This technique uses photomixing of the optical beat signal generated by a multi-mode laser diode in order to produce THz radiation [7–10].

Here, we present a portable and compact system based on THz QTDS which allows for outdoor-measurements of plants. Earlier experiments were performed in a laboratory under controlled environmental conditions. Despite the fact that well-defined climatic conditions have many benefits regarding the reproducibility of the experiment, the simulated conditions inside a laboratory will never fully resemble the real weather and the natural day and night cycle outside. Thus, outdoor experiments are a complementary addition to laboratory experiments. Besides, such experiments pave the way towards the envisioned compact, lightweight, battery-powered measurement systems for monitoring the water status of plants in the field and controlling their irrigation.

The THz QTDS spectrometer [8, 9] that we use for our outdoor measurements is based on a simple multimode laser diode and two photoconductive LT-GaAs antennas. The bandwidth of the resulting THz signal is limited to a few hundred GHz which is sufficient for our experiment. A mechanical delay line is used for scanning over the time-domain signal. To facilitate outdoor measurements, the electronics of the measurement setup are integrated in a compact and weatherproof housing. All parts can be powered from one single +12V supply voltage. Thus, battery operation of the setup is possible. Figure 1a shows a picture of the entire system in the garden. Figure 1b shows a close up of the THz beam path.

The measurements are controlled by a Raspberry Pi 2 Model B single board computer that is accompanied by a sound interface card for data acquisition. The lock-in process that is used for the data acquisition is implemented in software. In order to chop the emitter antenna electronically, the reference sine signal that is generated by the software is fed into a voltage amplifier that increases the signal amplitude from +/– 1V to +/– 20V. At the detector antenna, a trans-impedance amplifier is used to



(a) (b)

Fig. 1 **a** Photo of the measurement setup **b** Close up of the THz beam path convert the signal to a level that fits the dynamic range of the input of the sound interface card. This amplifier incorporates a low pass filter that cancels out parasitic signals at frequencies higher than the frequency of the reference signal. This filter helps to optimize the use the dynamic range of the A/D converter of the sound interface card. Reference and sample measurements are performed as a step-scan over a length of 40 ps with a stepwidth of 0.2 ps, which takes about 5 min. During data acquisition, the delay line stands still and the calculations for the software lock-in are performed stepwise, too, facilitating the implementation of this process on the Raspberry Pi. While the delay stage is moving, the setup draws a current of about 1.2 A. Thus, a 110 Ah car battery allows for nearly 4 days of off-grid operation.

The sample holder that carries the leaf is mounted on a servo motor that is controlled by the measurement software. Thus, it is possible to move the leaf in and out of the THz beam and, hence, to alternate automatically between sample and reference measurements. The movement range of the leaf is comparable to that of the plant when moved by the outdoor wind. So no excessive mechanical stress is imposed on the leaf.

To make the setup weatherproof, a cover made of robust tarpaulin fabric is placed over the spectrometer. The leaf is inserted into the measurement chamber trough a slit in the fabric. Above the measurement chamber the cover contains a transparent window to keep the leaf exposed to the sunlight. The trans-impedance amplifier is placed in the same housing as the spectrometer to minimize the length of the cable to the detector antenna. The other electronic parts of the setup are placed in a separate weatherproof housing.

The spectrometer was set up outside on a summer day. The pot with the corn plant that was used as a sample was placed next to the measurement chamber and one leaf was fixed on the sample holder (see Fig. 1 b). Even though in this case the plant was in a pot, this pot was kept in a fixed position throughout the experiment. So the plant could just as well have been situated directly in the ground. Over a course of 2 days and nights a measurement series was performed, taking a measurement on the leaf and a reference measurement about every 10 minutes. The amplitude of the reference measurements was checked regularly during the experiment and the adjustment of the photoconductive antennas was corrected when needed.

From the transmission values at 100–200 GHz shown in Fig. 2, it is obvious that the noise of the single-shot measurements is increased in comparison to earlier measurements in the laboratory [9]. But after filtering the data the change of the transmission trough the leaf can be observed over the course of the experiment. The progression of the transmission is very similar on both days, so we can conclude that we observe a reproducible effect. Yet, the observed effect seems unexpected at first sight. Higher transmission values correlate with lower water content of the leaf. The transmission is increased during the night giving hint to decreased leaf water content during that time. Intuitively one would expect a decreased leaf water content not during the night but rather during the hottest hours of the day with the largest natural light irradiance. A closer look at the graph reveals that starting from the morning there actually is a slight increase of the transmission during the afternoon that is followed by a decline in the evening. While this effect can be easily explained by the higher transpiration from the leaf due to the higher temperature and the state of the

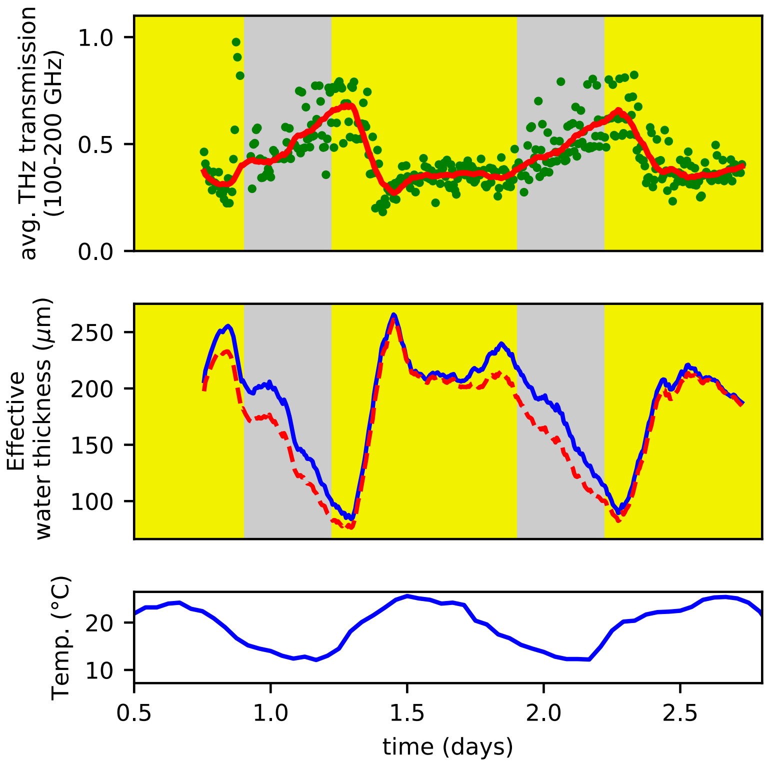


Fig. 2 Top: Transmission of the THz signal through the corn leaf over the course of two days and nights. The green dots represent the single THz spectra. The red curve was obtained by applying a Hampel filter to remove extreme outliers and a Savitzky-Golay filter for smoothing. The yellow and grey parts of the plot represent day and night based on the time of sunrise and sunset. Middle: Based on the THz transmission values the effective water thickness of the leaf is calculated. For the continuous curve, the actual outside temperature was used. For comparison, the calculations for the dashed curve were done assuming a fixed temperature of 26 °C. As the absorption coefficient of water is temperature dependent, the curves slightly differ with respect to the assumed temperature. Bottom: Outside temperature on the days of the experiment

leaf's stomata during these hours, it is much smaller than the effect mentioned before that we observe during the night. In search of an explanation for the much more pronounced effect during the night, a physiological effect in the plant should be considered as well as a purely physical explanation. Even though a loss of water at lower temperatures seems strange at first sight, it has to be taken into account that despite the fact that corn plants are accustomed to warm climates the temperature during the nights of the experiment dropped to values as low as about 12 °C. At these low temperatures, the functioning of the water transport in the plant is limited, which can include reduced water uptake by the roots and increased transpiration because the functioning of the stomata is disturbed [11]. This means that the observed water loss is not caused by increased transpiration but mostly by decreased water uptake from the soil.

Besides this physiological explanation, it should be considered that the absorption of THz radiation in water changes, too, depending on temperature [12]. Even if the water content stayed constant, a higher transmission would be observed at lower temperatures. This means that both effects contribute to the observed phenomenon in the same direction. To separate the physiological effect from the physical effect, we use a model based on the effective medium theory of Landau-Lifshitz-Looyenga to calculate the water content of the leaf [13, 14]. In this model we include the dependency of the dielectric properties of water on the temperature.

The values of the temperature were taken from the weather recordings of the days of the experiment [15]. For comparison we did the same calculations pretending the temperature had been at a constant value of 26 °C throughout the experiment. The change of the curve's slope from the uncorrected to the corrected calculations is obvious in the plots in Fig. 2. Yet, the overall shape of the curve does not change substantially. Thus, we conclude that the main part of the observed effect is of physiological origin.

Overall, we have demonstrated that THz QTDS measurements can be performed outside under field conditions. To our knowledge, this is the first time that a THz time domain setup has bee used in this way. Tackling the difficulties of outdoor measurements in comparison to laboratory experiments is rewarded with the observation of effects that were not predictable from earlier laboratory experiments.

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