Distributed Humidity Sensor for Moisture-Front monitoring in Soils

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Abstract: In this contribution, high spatial resolution distributed humidity sensing was demonstrated for moisture-front monitoring in soils by using polyimide coated optical fiber.
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1. Introduction

The soil moisture play a key role in the hydrological cycle because it responds dynamically to the alternation of rainy periods and dry periods [1], [2]. After a rainy period, the upper part of the soil is filled with water as a result of infiltration. On the other hand, during the dry periods, the water contained in the soil profile is evaporated and redistributed due to the evapotranspiration and to the potential gradients, respectively. The characterization and measurement of the moisture content of the soil profile is crucial for many applications related to the balance of water and contaminants, such as the application of hydrological models, irrigation programming [3], etc.

The currently most used methods are based on relating the dielectric constant, ε, of the soil matrix to the volumetric content of water, $\varepsilon=f(\theta)$. It can be with a moisture sensor that employs time-domain reflectometry (TDR), or with a capacitance sensor [4], [5]. In recent times, the use of capacitive sensors has been extended due to their good performance and low cost [6]. This type of probes does not take punctual measures, but rather integrate the area corresponding to the influence of the sensor, which may vary according to its length. Therefore, in this case the soil moisture profile can only be measured with a low spatial resolution.

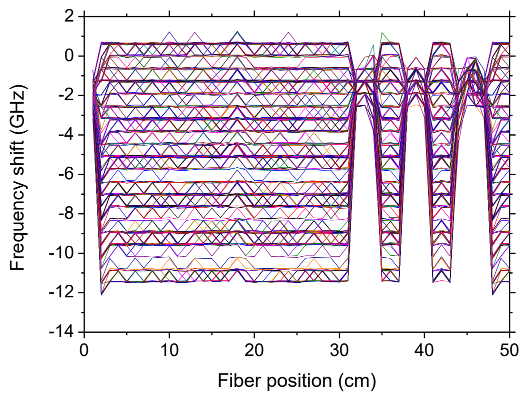
Fiber optic sensors represent an interesting alternative to these conventional sensors due to their particular properties such as their immunity to electromagnetic interference, small size and operating capacity in hostile environments, as highlighted in [7]. In addition, the fiber optic sensor presented in this work, has the great advantage of being able to measure soil moisture in a distributed way with a high spatial resolution.

Distributed fiber optic sensors (DFOSs) seems to be an appealing technology to provide continuous measurements along optical fibers. Thus, these techniques are especially interesting for structural health monitoring of large structures such as bridges, oil pipelines, and dams, among others [8]. On the other hand, approaches based on optical frequency-domain reflectometry (OFDR) analysis allow the distributed measurement in the fiber at shorter distance with high spatial resolution. The small size of fiber and the capability to be embedded, together with the high spatial resolution achieved make them a good candidate for moisture monitoring. For this application, other authors explored the distributed humidity sensing before [9], [10]. In particular, in [10] was characterized the sensitivity of optical fibers with different buffer using an optical backscatter reflectometer (OBR). Also, the capability of measuring moisture in soils using optical fiber sensors attracted the interest of other scientists [11]–[13].

In this contribution, we present a distributed fiber optic sensor to study the moisture-front evolution in controlled laboratory conditions.

2. Experimental setup

For the proposed distributed moisture sensing application, we choose a polyimide coated fiber from Fibercore (SM1250(10.4/125)P). This fiber was studied in [3], showing the highest humidity sensitivity in a comparative analysis. Before designing the moisture-front sensor demonstrator, we characterized the fiber in a climatic chamber. As the distributed feature of the fiber was not previously demonstrated, we also created a fiber structure to confirm the distributed sensing capability of the fiber. A 50 cm sensing fiber was used and three sections of 5 cm were covered with heat shrink fusion splice protectors to reduce significantly the humidity sensitivity of these sections. Fig. 1 and 2 present the characterization results of the fiber when inserted in a climate chamber at constant temperature of 35 ºC and a relative humidity (RH) stepped variation of 30 min from 30% to 90% and *vice-versa.*



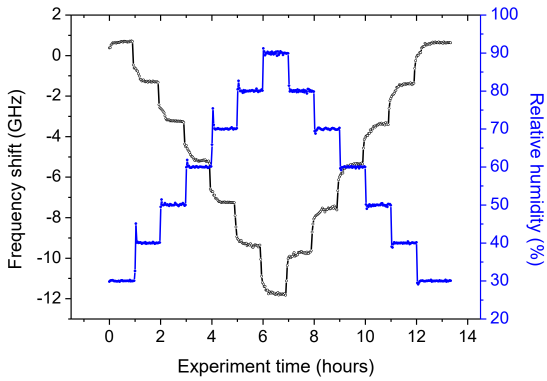


Fig. 1 Distributed humidity response along the fiber when interrogated with the OBR 4600 for the different %RH in the climate chamber.

Fig. 2. Humidity sensor response and the climate chamber humidity readings along the time when the humidity characterization was performed.

Fig 1 demonstrated the distributed sensing ability of the fiber. At the covered sections, the variation was negligible. Figure 2, on the other hand, present the comparison between the chamber humidity read with the frequency shift measurement obtained with the OBR from the first fiber section. In this figure, small sensor hysteresis was measured. For this study, this effect can be neglected as the dynamics of the moisture-font evolution is relatively slow.

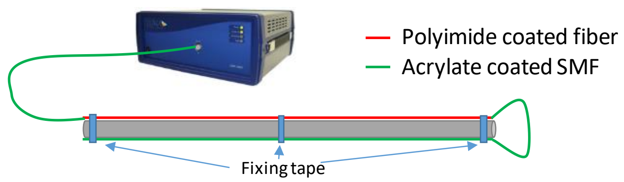


Fig. 3. Schematic diagram of the moisture-front sensor design.

Once the fiber was characterized, the experimental setup was prepared for the demonstration of the moisture-front monitoring. As illustrated in Fig 3, The OBR 4600 (LunaTechnologies INC.) was connected to two sections of sensing fibers. The first section was the polyimide coated fiber and following, it was fused an acrylate coated SMF. The aim of this second fiber is to act as a temperature compensating fiber due to its negligible sensitivity to humidity [2]. Fibers were positioned in a methacrylate guiding bar and were fixed at three points with fixing tape. The sensing distributed transducer was installed inside a cylinder designed for the moisture-front sensor demonstration. It consists of a 15 cm diameter, 1.5 m long PVC tube, in which the sensing bar was placed in a central position (Fig 4(a)). Next, five commercial electrical humidity point sensors (Decagon EC-5) were placed evenly spaced along the tube. Then, the tube was filled with silica sand and compacted to homogenize the sand distribution and allow a correct moisture-front displacement. This silica sand is specified for its use in pool filters, water purification and sports fields and its characteristics are presented in Table 1. In order to start the experiment, the fibers were connected to the OBR 4600 and the system was calibrated.

Table 1: Characteristics of the porous media.

	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	*Cu*	*Cc*
Sand (100%)	0.22	0.45	0.76	3.49	1.20

Cu: Coefficient of uniformity. *Cc*: Coefficient of curvature. d_i: diameter where *i* percentage of the material is lower than the value.

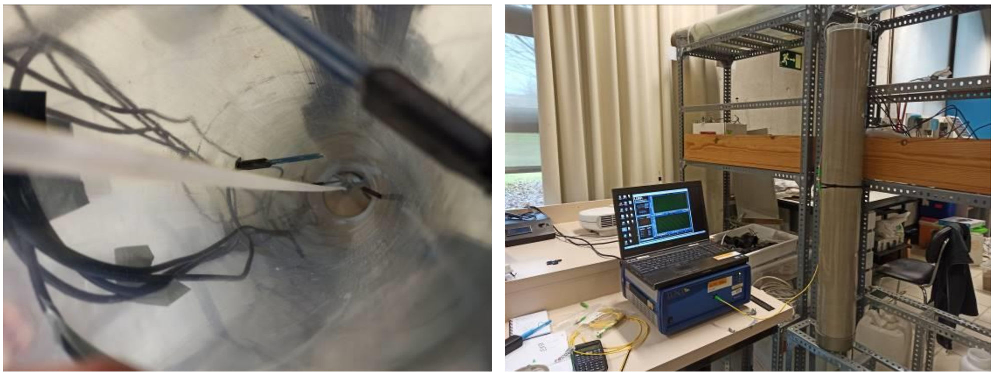


Fig. 4 Pictures of how the guiding bar with the sensors was placed inside the 15 cm tube and the experiment ready for the moisture-front monitoring experiment.

Fig. 5. Pictures of the guiding bar with the sensors sticking out from the sand-filled tube and the initial water spill.

3. Results

In order to initiate the experiment, 1 L of ambient-temperature deionized water was spilled slowly to simulate a rainfall. This liter of water was calculated to infiltrate to an initial depth between 17-20 cm. After the pouring, as expected, there was a fast infiltration of the water down to the initial 20 cm as depicted in Fig. 5(b). It can also be seen in the picture that the infiltration is not perfectly homogeneous, probably due to an uneven sand compaction. The initial saturation zone can also be seen in Fig. 6(a), with the first 20 cm suffering no frequency shift. This is because the calibration and the start of the measurements was done right after finishing the water spilling.

A custom Matlab script controlled the setup and performed automatic measurements each 32 seconds, obtaining the frequency shift for the regions of interest with a spatial resolution of 1 cm. The results retrieved for the first 17 hours are presented in Fig. 6(a). This colormap represents the frequency variation along the polyimide fiber down to 75 cm, after being compensated with the information retrieved from the acrylate-coating fiber. First, it can be clearly seen the moisture-front moving down the tube at a decreasing speed. On a side note, the fixing tape employed to hold the fiber can be seen around the 55th cm.

The profile of the moisture-front has been extracted to Fig. 6(c), showing a behavior that matches with the data provided by the commercial probes. The position of the first probe was at 5 cm-depth, so it was almost instantly saturated. The second probe, located at 32.5 cm presented a step increase in the detected volumetric water content, up to 0.15 mm^3(water)/mm^3, about 3 hours after the experiment start (then showed a constant decrease to 0.1 mm^3(water)/mm^3). This perfectly matches the measurements obtained using the optical fiber. The third sensor located at 60 cm-depth is not included in the graph because the moisture front reached its position around at around t=30 h. Fig. 6(b) depicts the probe 3 response, evidencing the arriving of the moisture front at around t=25 h with a slow increase up to 0.1 mm^3(water)/mm^3 in t=50 h. Figure 6(b) also represents the data provided by the OBR, with a 5 samples smoothing in time. Both evolutions seem to agree, but the optical fiber based solution presents a noisier profile and a more unstable behavior. This effect could be due to many factors such as temperature-compensation errors, pressure effects in the fiber or sudden polarization changes. Also, it should be considered that the reference probes Decagon integrate the water content in a volume about 5 cm long of the tube. Conversely, the optical fiber only reacts to the water content when direct contact is achieved. In this manner, an inhomogeneous moisture front due to an uneven compaction could be detected. Finally, the moisture-front did not reached probes 4 and 5.

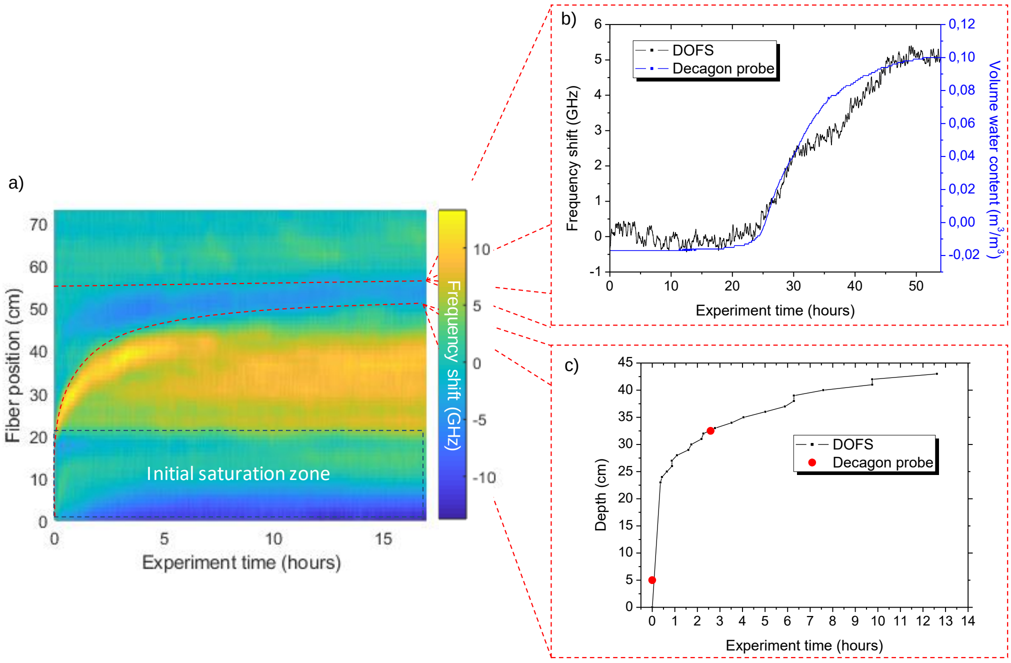


Fig. 6. a) Moisture depth evolution along the experiment time. b) Comparison between commercial capacitive sensors and the result from the corresponding section of the proposed DFOS sensor. c) Moisture-front evolution obtained with the distributed sensors and first readings from the Decagon sensor

4. Conclusions

In this contribution, we experimentally demonstrated the potential application of DFOSs for moisture-front monitoring in soils. A polyimide humidity sensitive fiber was used for the distributed moisture detection and an acrylate fiber placed next to it was used for the temperature compensation. It has been demonstrated the ability of the system to accurately detect the movement of the moisture front, agreeing with the results provided by the point electrical probes. The initial detection of the moisture-front seems to be affected by temperature, probably due to temperature compensation mismatches. However, it is likely that other effects are affecting the frequency shift readings provided by the OBR, such as pressure, polarization changes, etc. Further work is being done in clarifying these aspects.

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