Intelligent Irrigation System for Low-cost Autonomous Water Control in Small-scale Agriculture

Deliverable D3.6b

Second report on evaluation and KPI assessment in pilots

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Executive Summary

To measure soil water content in real time, INTEL-IRRIS has decided to use a capacitive soil moisture sensor from DFRobot Gravity company model 'SEN0308'. To be able to use them efficiently, i.e. collect accurate data for making accurate irrigation recommendations to small holders, the performances of these sensors were firstly tested in the laboratory. This document is separated in 4 sections with different objectives:

1. **to remind the physical principles of the capacitive sensors** and how they measure the moisture content of their environment.

2. **to highlight the specific constraints and limits when the environment is a cultivated soil,** and in particular in the Mediterranean area,

3. to present the tests made in controlled conditions (laboratory) in order to highlight SEN0308 performances and weaknesses, and also compare these performances to those of a previous capacitive sensor from DFRobot that is 4 times cheaper.

4. **to make some recommendations** on what to look out for (i) when installing the sensors in the field and then (ii) during the period of field monitoring in order to avoid mistakes and check and improve the probe performances in our specific context.

1. **The physical principles of the capacitive sensors**

The capacitive sensors consist of 2 conductive elements separated by a di-electric, i.e. an element with no conductivity, which acts like an electric capacitor. When electricity is sent to the circuit, even if the di-electric does not conduct electricity nevertheless it is submitted to the magnetic field created by the electrical current. This magnetic field influences the di-electric not at the macroscopic scale but at the scale of the molecules kind of the energy provided by the field. The sensors measure the dielectric permittivity which is expressed in an electrical tension (in volt). The relative permittivity of pure water is approximately 80 when it is around 10 for rocks or clay and around 5 for organic materials. This specific value for water comes from the fact that H2O is a polarized molecule which can easily rotate when put in the magnetic field. As the output signal from water is much higher than any other constituent found in a natural environment, the general concept is to consider the output signal proportional to the amount of water close to the sensor and then to calculate the volumetric water content.

2. **The constraints and limits of capacitive sensors in soils**

The quality of the output signal depends on:

- the frequency signal: the lower the frequency and lower the quality. It is considered that frequencies > 1 GHz are necessary for accurate measure as it is the case for TDR probes. But TDR probes are too expensive for small farm holders and capacitive sensors that are much cheaper have frequencies of some hundreds of kHz, thus the interpretation of the signal needs calibration.

- quality of probe insertion: the volume of soil taken into account by capacitive sensors is quite small, thus when inserting the sensor in the soil, it is necessary to keep the soil structure undisturbed (keep the way the particles are organised in space). Otherwise, in case of disturbances (creating large voids or creating compacted volume) there is a risk that soil

volume around the probe is no more representative of the core volume (large pores could increase the volume of air and thus decrease the volumetric water content; on the opposite: compacted volumes could have higher water content compared to the bulk soil.

- the clay content: the clay minerals have a large specific area (50 to 600 m^2/g) that are negatively charged. On the clay minerals surface one can observe a double diffuse layer (DDL) that is an ionic structure that describes the variation of electric potential near these charged surfaces, and which behave as a capacitor s.

- the soil temperature: the permittivity increases as the temperature increases.

- water salinity: the permittivity of saline solution is higher than that of free water so that every increase in salinity gives the wrong feeling of an increase in water content.

3. SEN0308 performances in controlled conditions

The SEN308 model has indication of minimum and maximum insertion depth. Our experiments have shown that the maximum insertion depth must be systematically used as it provides higher sensitivity to the changes in water content.

Unlike what was expected according to the theory, the output signal was not sensitive to temperature changes (in the range of 10-40°C). This is perhaps because the sensor is already designed to take these changes into account. Nevertheless, some surprising changes in the signal were observed when the sensors were left under direct sunlight. Additional experiments must be conducted to confirm this observation; at the moment our hypothesis is that excessive heat of the electronic parts could result in these unexpected signal changes.

Calibration procedures were used to test the performances of both SEN0308 and SEN and SEN0193 models. With the SEN038 the performance was significantly increased with a much wider range of output signal, higher sensitivity to measure the water content and detect changes.

When making calibration (i) in a saline solution (16 g/L of NaCl in distilled water) or (ii) in a sand wetted with the saline solution, the output signal was decreased, that could be wrongly interpreted as an increase in water content. This impact of the saline solution in our experiment is consistent with the theory.

When the sensor was tested with wet clay (wetting with distilled water) the signal indicated a water saturation when the gravimetric water was 60% or higher. Complementary experiments will be conducted with a control of bulk density to see if this is consistent with the gravimetric water content.

To obtain the performances described above, another important factor to control is the charge of the batteries. Below 3.0V the output signal can be altered and wrong conclusions could be made about the soil water content.

4. Recommendations for using the capacitive sensors in the fields

Our recommendations concern the insertion, the calibration and also a suggestion about using both SEN0308 and SEN0193 to monitor simultaneously (i) the water content in the layers that where the plant root system is locate and (ii) the drainage (if any) below the root system as it this water could be considered as wasted.

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1. INTRODUCTION

Efficient irrigation requires the use of innovative technological decision-making devices. Soil moisture probes are one of these instruments. To measure and describe water in the soils, **two main models of sensors are currently available on the market**:

- **those estimating water potential**, all of them being based on the principles of tensiometry,

- **those estimating the water volumetric content based on soil dielectric permittivity**.

Technologies based on dielectric permittivity include again two types of methods:

- **time domain reflectometry (TDR)** which are expensive and used by researchers but not affordable in the context of small holders;

- **frequency domain reflectometry (FD),** including capacitive methods, which are much cheaper and new models are constantly available.

These two technologies (TDR and FD) are often confused because they both measure the dielectric permittivity of the soil around the probe and then deduce the soil moisture content. FD sensors (include capacitive sensor) are the one we are interested in; as they are derived from the former, thus TDR will also be shortly described.

All these sensors are often presented as " highly reliable " by the companies making and selling them, however, they have various limitations that it is important to be aware of in order to avoid errors of interpretation and thus inaccurate decisions.

The aim of this document is to present:

- 1st part: the theoretical and practical principles of capacitive sensors measurement,

- 2nd part: the use of capacitive sensors to measure the soil water content, their qualities and limits,

- 3rd part: the laboratory tests of the capacitive sensors selected to be used in the project.

- 4th part: recommendations on the use of these sensors in the field for irrigation recommendations.

2. Theory and technical principles of capacitance measurements

This first part provides information on the general physical principles related to the capacitance measure and the technical principles of the tools used to do that measure.

2.1. The concept/definition of dielectric permittivity

Dielectric permittivity (unit: pF m^{-1} or 10^{-12}F m^{-1}) is a physical property that describes the response of soil to an applied electric field. To represent the permittivity ε of a medium other than vacuum, a quantity called relative permittivity of "dielectric constant" (ε_r) is used. This unitless quantity relates the permittivity of the medium to the permittivity of vacuum ε_0 (Robinson et al, 2088, p363, left):

$$\varepsilon r = \frac{\varepsilon}{\varepsilon 0}$$

Each type of material has a characteristic dielectric constant:
- ε_r = 1 for vacuum (by definition)
- $\varepsilon_r \approx$ 1 for air
- ε_r = 2 to 7 for wood and organic materials,
- ε_r = 8 to 14 for stones and clays,
- ε_r = 78.3 for free water (at 25°C),

2.2. The factors affecting the permittivity measurement

The permittivity is measured using a 'RC' circuit, i.e. resistance/capacitor circuit. The permittivity of a homogenous material is related to the electrical polarizability of the molecules or atoms making up the material.

The figure shows the orientation and polarisation of dipole water molecules in a plate capacitor.

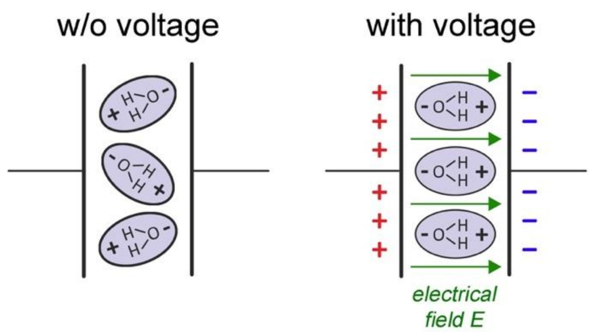


Figure 1: schematic presentation of the water molecules between the plates of a capacitor in absence (left) and presence (right) of an electrical field.

An important aspect of permittivity measures is that in a dielectric medium, there are always dielectric losses, i.e. energy dissipation (in the form of heat for example, (Awati, 2022)). These losses can be estimated by defining a relative complex permittivity (Topp et al., 2000)

$$\epsilon_r^* = \epsilon_r^{'} - j.(\epsilon_r^{''} + \frac{\sigma_{DC}}{2\pi.f.\epsilon_0})$$

Where:

- ε^*_r is the apparent permittivity measured by the probe
- ε'_r is the real part of dielectric permittivity: the energy stored or buffered by the soil. It is a characteristic of dry soil and its volumetric water content
- ε''_r is the imaginary part and represents the "dielectric loss"
- σ_{DC} the conductivity of the substrate at a given frequency
- f is the frequency of the electric field
- ε_0 the permittivity of vacuum

When having the objective of estimating the soil water content, we would like to measure only ε'_r that is the real part depending on water content. With the probes currently on the market, this is not yet possible. The probes on the market can only measure the apparent permittivity, i.e. the sum of the real and the imaginary permittivity.

As shown by the equation, the imaginary permittivity is affected by:

- σ_{DC} the conductivity of the substrate that is controlled by the salt concentration in the soil solution: if the concentration is high enough to affect the soil conductivity, it can result in a significant imaginary permittivity, creating a bias for the measurement of the water content. (the second part will explain this process)

- ε''_r dielectric loss/dielectric dispersion increases with increasing humidity and increasing clay content.

- f is the frequency of an applied electric field (as observed in the above equation is called "dielectric dispersion".

The frequency factor is extremely important: the higher the frequency and the lower the dielectric dispersion, the more reliable the measurement. Most studies on the subject consider that the effect of frequency and dispersion is relatively large between 1 and 200 MHz and negligible above 500 MHz (Robinson et al., 2008).

2.3. Empirical model linking water content and permittivity: the Topp model

All the TDR and capacitive technologies consist of measuring the dielectric permittivity of the soil and then approximating the water content ($\boldsymbol{\theta}$) by using empirical relationships. These empirical relationships are often third-degree polynomial regressions of the type:

$$\theta = a.\epsilon_a^3 + b.\epsilon_a^2 + c.\epsilon_a + d$$

With ε_a the apparent dielectric permittivity measured by the sensor.

(Topp et al., 1980) determined an empirical polynomial regression by relating dielectric permittivity to water content:

$$\theta = 4,3.10^{-6}.\epsilon_a^3 - 5,5.10^{-6}.\epsilon_a^2 + 2,92.10^{-2}.\epsilon_a - 5,3.10^{-2}$$

This model was presented as valid for a large number of soils (the paper from Topp et al. 1980, was cited nearly 6 700 times…) and is indeed still widely used today with TDR as well as capacitive sensors (Visconti et al., 2014).

Nevertheless, alternative relationships proposed that consist mainly in 2 types of models:

- ‘one-parameter models’, linking water content to only permittivity

- ‘semi-empirical mixed models’ trying to approximate water content (θ) through permittivity but also through other parameters related to the characteristics of the solid matrix, such as soil bulk density (that allow to calculate the porosity), size and shape of the solid particles, permittivity of the soil solutions and its matric potential.

2.4. The TDR (time domain reflectometry) sensors

TDR uses very high frequencies (> 1 GHz) so that the permittivity measurement becomes independent from the used frequency. Losses and dispersion are low with imaginary permittivity which is negligible compared to real permittivity. High frequency TDR is also not very sensitive to the electrical conductivity of the medium (i.e. soil salinity), nor the soil texture and temperature.

TDR probes are widely recognized for their high measurement accuracy in many soil types and they are considered as the most reliable. But this technology has a high cost due to the use of high frequencies and the complexity of the components which require high quality materials. Similarly, the interpretation of the signal is complex and requires either the use of a complex signal processing.

On a technical point of view, it is also necessary to mention that TDR technology requires a large power supply, often requiring the use of solar panels and large-capacity batteries.

2.5. The capacitive sensors

2.5.1. Physical principle

The capacitive method is also based on the estimation of the relative dielectric permittivity of the soil. This is estimated by measuring the charging time of a capacitor that uses the soil as a dielectric.

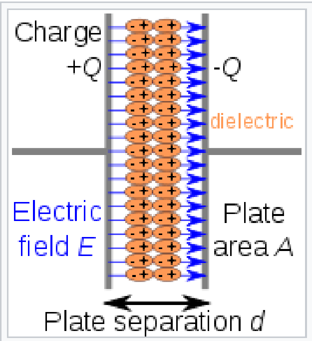


Figure 2: schematic presentation of a capacitor plate, the dielectric in the middle of the plates and the electric field with the molecules’ polarisation.

In the capacitor, charge separation in a parallel-plate capacitor causes an internal electric field. A capacitor dielectric (or simple 'dielectric', in orange on the figure) can reduce the field and increase the capacitance (i.e. the ability of this system to store an electric charge).

A high permittivity allows a greater stored charge at a given voltage. This can be seen by treating the case of a linear dielectric with permittivity ε and thickness *d* between 2 conducting plates with uniform charge density σ_ε. In this case the charge density is given by:

$$\sigma_\varepsilon = \varepsilon V d$$

and the capacitance per unit area by:

$$C = \sigma_\varepsilon V = \varepsilon d$$

From this, it can easily be seen that a larger ε (dielectric constant) leads to greater charge stored and thus greater capacitance.

For a planar capacitor, the electrical capacitance (in Farad) is a function of the dielectric permittivity (Farad/cm) of the medium between the plates and can be calculated using the following formula (Rial and Han, 2000):

$$C = \frac{\epsilon . A}{S}$$

Where:

A is the area of the plates (cm²)

S is the distance between the plates (cm) [it is the same as 'd' in the previous equation]

2.5.2. The technical characteristics of the capacitive sensors

Commercial capacitive sensors sold for measuring soil water content are not plane capacitors. They simply consist of 2 copper traces that *act* like a capacitor!

This "capacitance effect" is a 'side effect' that happens in all circuits and which is generally undesirable and made negligible to avoid negative effects. But by making the two copper traces deliberately large on an 'inert' support: epoxy insulating plate. This effect can be exploited to measure the soil capacitance and thus to estimate the changes in soil volumetric water content. This is made possible because the capacitance will then only depend on:

- the characteristics of the copper traces,

- the characteristics of the environment around the sensor (the *dielectric*) i.e. the soil in which the water content is the most fast changing parameter.

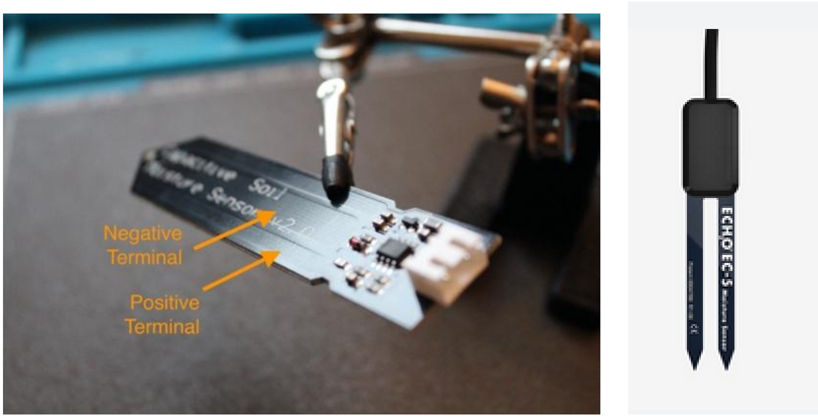


Figure 3: Left: a capacitive soil sensor formed by two large copper traces applied on an inert support and covered by a similar inert material (epoxy resin and fiber glass). Right : another popular capacitive sensor (EC5, Decagon company) for which the 2 copper traces are located in separated branches and the dielectric (the soil) is not only located around the copper traces but also between.

Finally, even if capacitive sensors are not exactly plane capacitors, the above equations remain valid regardless of the geometry of the plates.

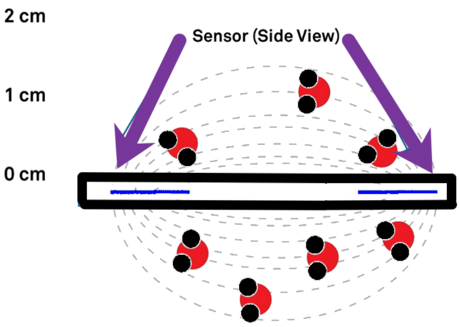


Figure 4: Schematic view of (i) a capacitance sensor with the 2 copper traces embedded in an epoxy material, (ii) the electrical field and (iii) the polarisation of the water molecules in the vicinity of the sensor.

2.5.3. The advantages of the capacitive method

The cost of capacitive sensors is relatively low (especially when compared to TDR probes), which makes it possible to instrument field without a low budget or (if keeping the same budget) by increasing the sensor's density in a given field.

Moreover, their power consumption can be very low and some require low excitation voltages to operate (as low as 3 volts) which allows for a high autonomy with reasonable battery capacities. Finally, they are also relatively easy to install.

2.6. Conclusion

The disadvantage of the capacitive method is that the signal is difficult to interpret in the absence of additional information, on the sensor itself and the characteristics of the environment, i.e. soil characteristics (mainly clay content) and the concentration of dissolved minerals, as we will see in the next section.

3. Capacitive measurements in a soil: constraints and limits

The previous sections have explained how a capacitive sensor can measure the permittivity of a dielectric in its environment. The first section has also presented the dielectric constant of different materials (εr = 1 for vacuum and for air, 2 to 7 for wood and organic materials, 8 to 14 for stones and clays, around 80 for water).

We have also seen that the quality of the output signal depends on the frequency signal: the lower the frequency and lower the quality (some part of the energy of the electromagnetic field is dissipated in heat). It is considered that frequencies > 1 MHz are necessary to avoid this dissipation, but such instruments are expensive.

In our project dealing with small holders, the equipment cost is a limiting factor and consequently it is capacitive sensors that will be used even if they have frequencies of only some hundreds of kH. At those frequencies signal dissipation is not negligible and the soil dielectric permittivity can be affected by different factors. This section will present the factors affecting the measurement of soil dielectric permittivity with capacitive sensors and thus highlight the limits and constraints of such devices.

3.1. The soil as a dielectric: its specific characteristics

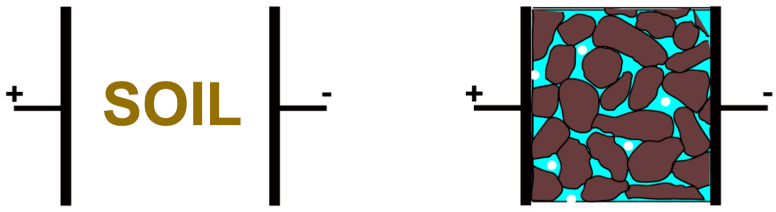


Figure 5: Left: schematic view of a soil in capacitor. Right: schematic view of the mineral fractions of a soil and the water located in the porosity.

The soil is a porous media in which:

- the solid phase is made of mainly mineral material mixed with a small amount of organic material;

- the mineral phase consists in a mixture of (i) large mineral fragments (from 2 microns to 2 mm) (ii) phyllosilicates or clay minerals with large specific surfaces and which have surface charges (mainly negative);

- the pore volume between the solid particles is occupied in varying proportions by air and water,

- some of the water can pass through the soil in the largest pores under the effect of gravity, some part of the water is retained by capillary forces in the smaller pores and some water is even hold more tightly at the surface of the mineral as we will see in this section,

- the water in the soil is never pure (i.e. made only of H2O molecules), but it contains ions (resulting from the dissolution of various mineral elements) in very various concentrations and this concentration can change over time (from some hours to several months).

Despite this heterogeneity, as a first approach, it can be considered that the soil overall dielectric behaviour is largely controlled by the volume of water. If we considered that (very roughly) that the dielectric constant would be around 80, 5 and 1 for water, mineral particles and air, respectively, the next figures illustrate the importance of water content in the global dielectric constant of a model soil (i.e., 50 sand and silt particles and 50% of porosity filled with various amount of water).

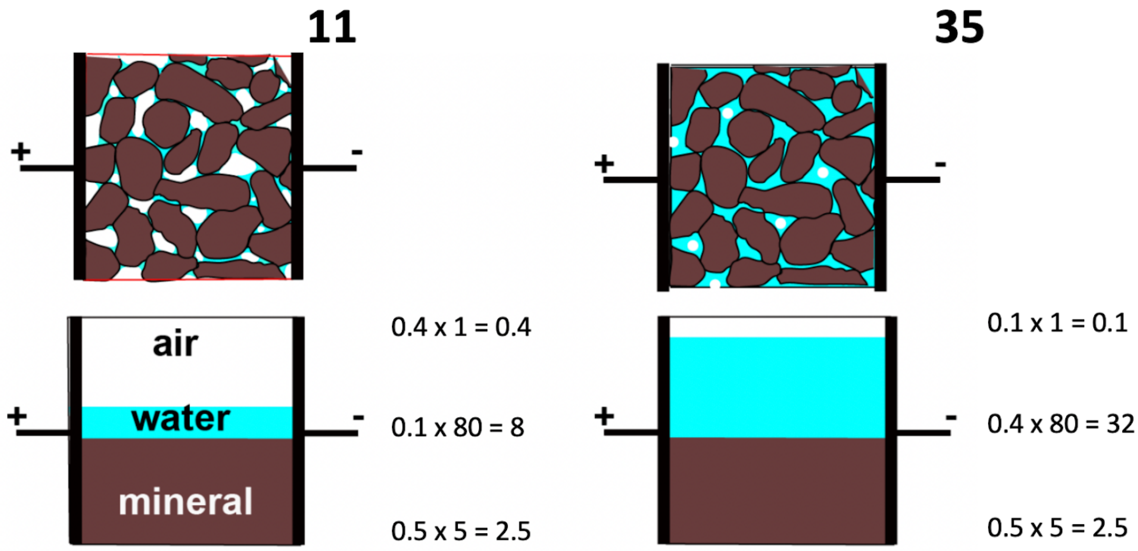


Figure 6: calculation of the dielectric constant of the different volumes (right side of the figures) and the global dielectric constant (number on the top, in bold), for dry (left) and wet soil (right).

The next paragraph presents different factors that affect the soil permittivity and thus make it more complex to estimate accurately and precisely the water content and thus make relevant irrigation decisions.

3.2. Probe insertion

The volume of soil taken into account by capacitive sensors is indeed quite small: a distance of some cm around the sensor. Consequently, when inserting the sensor in the soil, it is necessary to keep, as much as possible, the soil structure undisturbed, i. e. keep the way the particles are organised in space. In case of disturbances (creating large voids or creating compacted volume) there is a risk that soil volume around the probe would no more representative of the core volume (large pores could increase the volume of air and thus decrease the volumetric water content; on the opposite: compacted volumes could have higher water content compared to the bulk soil). The next figure illustrates the consequence of incorrect insertion

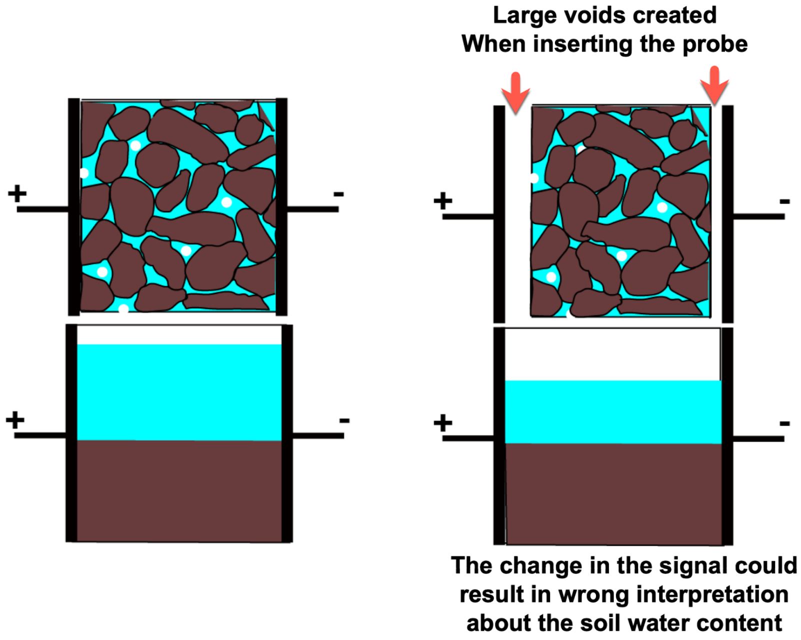


Figure 7: The impact of soil disturbance when inserting the probes in the soil.

The farmer will perhaps need to take the probe out of the soil during the growing season and then he has to minimise the disturbance, deciding to re-insert the probe in the same hole or to reinsert it in a nearby position; this has to be decided In each situation. Even if soil disturbances are kept as low as possible, it must be noted every time a probe is inserted in a soil the disturbances are different and largely unpredictable. Consequently, the most important is that farmers inform the researchers that the probe has been moved, and if possible take pictures of the old and new locations.

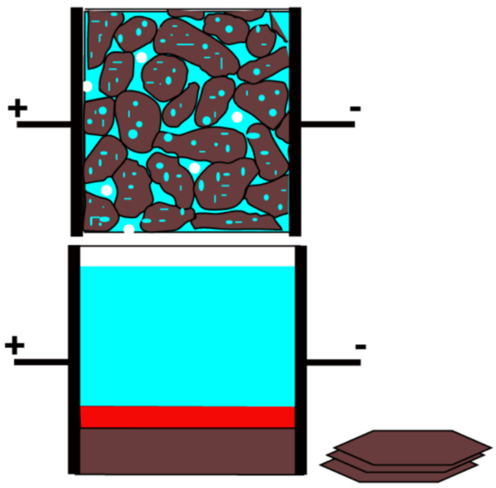
3.3. Clay content

The water is held in the soil by capillary forces occurring for pores having equivalent diameter < 20 microns approximately (in larger pores, the water is draining to a deeper layer at various velocities, some minutes to some hours). But they are also surface forces that hold one to several layers of water molecules with higher forces.

Firstly, the hygroscopic water is moisture in the form of a molecular membrane that is adsorbed on the surface of soil particles due to the adhesive forces that control the wettability of the surface. Consequently, the hygroscopic water can be observed at the surface of sand and silt particles.

Secondly, on the surface of the clay particles, there is a 'diffuse double layer' (DDL). The DDL is an ionic structure that describes the variation of electric potential near a charged surface, i.e. clay minerals. **What is important to note, is that the DDL behaves as a capacitor (Mojid, 2011).** The amount of water in DDL cannot be precisely measured but it is proportional on (i) the surfaces developed by the clay mineral and (ii) the amount of charges on the clay surfaces.

If sand and silt particles have low specific surfaces (from one to several m^2/g) and have no surface charges, clay can have specific surfaces from 50 to 600 m^2/g and charges ranging from 5 to 60 meq/100 g. Consequently, in clayey soils, the amount of water in the DDL can be far from negligible and will not behave as ‘free’ molecules in the main part of the soil solution. Consequently, in case of significant amounts of water in the DDL, the amount of water is not correctly estimated if no specific correction is done to take into account the specific behaviour of the water molecules located in the DDL.



The upper figure shows the soil aggregates made from clay particles. The blue colour highlights the fact that it is held by capillary forces inside and outside the aggregates.

As the solid phase is made by aggregates, some of the water molecules constitute the double diffuse layer (DDL). The permittivity of these molecules is different (lower) than the permittivity of the ‘free’ water. Consequently it is not detected by the capacitance probes and the amount of water is then incorrectly estimated.

Figure 8: in clayey aggregated soil, some part of the water is located on the clay surfaces ((presented in red) and has a different dielectric constant

3.4. Temperature

Permittivity increases with increasing temperature which is likely due to the increase in dipole mobility. Water relative permittivity is *approximately* 80 at 20°C and is falling to approximately 73 at 40°C.

3.5. Water salinity

When speaking about the water in soil, it is common to refer to “soil solution” because soil never contains pure water, they always contain solutes, i.e. anions and cations in solution. In Mediterranean irrigated fields, the amount of solutes can be significant and the concentration can increase drastically, especially close to the soil surface where sometimes salt crust can be seen if the evaporation is high enough. The water molecules submitted to an electrical field behave differently in absence and presence of solutes and the difference depends on solute concentration.

The electrical conductivity of saline water is a function of the salt content (salinity) and temperature. At frequencies below 1 GHz its value is given by the expression:

$$\sigma = 0.18\, C^{0.93}\, [1 + 0.02\, (T - 20)] \qquad \text{S/m}$$

Where C is the salt content in parts per thousand and T is the temperature in degrees Celsius.

(https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjf8-3hluz8AhX51XMBHRSFAD4QFnoECAkQAQ&url=https%3A%2F%2Fwww.itu.int%2Fdms_pubrec%2Fitu-r%2Frec%2Fp%2FR-REC-P.527-3-199203-S!!MSW-E.doc&usg=AOvVaw2MM4JST-4oNqNYTNuYoLmt)

In the cultivated soil, (Thompson et al., 2007) observed a relative increase of 4 to 7.5% in estimated soil water content for each 1 dS m^{-1} increase in electrical conductivity of the soil water.

3.6. Stony soils

Stones and gravels (i.e. mineral elements > 2 mm) will make it difficult to enter the probe in the soil. They will also make it difficult to measure the soil bulk density which is indeed necessary to link volumetric and gravimetric water content.

Some specific experiments will have to be conducted to evaluate the impact of stone and gravel in the vicinity of the SEN0308 sensor.

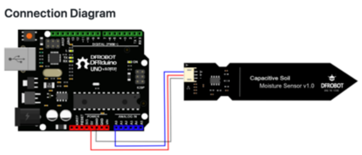
4. CHARACTERISTICS OF THE SEN0308 CAPACITIVE SENSOR (DFROBOT COMPANY)

Two models of capacitive sensors built by the DFRobot company are commonly used at the moment: SEN0193 & SEN0308 which cost around 5 & 20 euros, respectively.

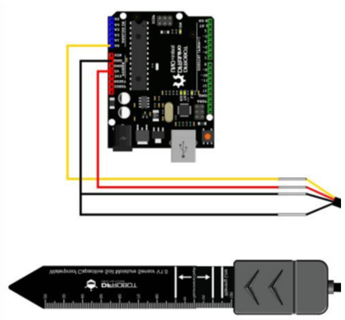
Compared with the SEN0193 version, the SEN0308 sensor has increased waterproof performance; as it can still be used after being immersed in water according to DFRobot. With an increased plate length, the capacitive electrode plate has increased length (from to 12cm approximately) to measure more accurately the soil moisture (in addition, the circuit performances are presented as optimized). Finally, the sensor has a wide input voltage (3.3V-5.5V) and is compatible with Arduino, ESP32, micro:bit, control board, Raspberry Pi and other common control boards.

For complementary details concerning the 2 sensors see:

https://wiki.dfrobot.com/Capacitive_Soil_Moisture_Sensor_SKU_SEN0193
https://wiki.dfrobot.com/Waterproof_Capacitive_Soil_Moisture_Sensor_SKU_SEN0308



SEN0193



SEN0308

Figure 9. Photography of the 2 models of capacitive sensors that were tested and their connection to the Arduino microcontroller.

This section will present the main results of different tests that have been conducted at IRD soil physics laboratory. The objective of those tests was to evaluate the impact of factors affecting the signal of the SEN0308 sensor (temperature, soil insertion depth) and to compare some of its performances with those of the SEN0193.

4.1. Overview of SEN0308

The next figure shows some details of the SEN0193 sensor.

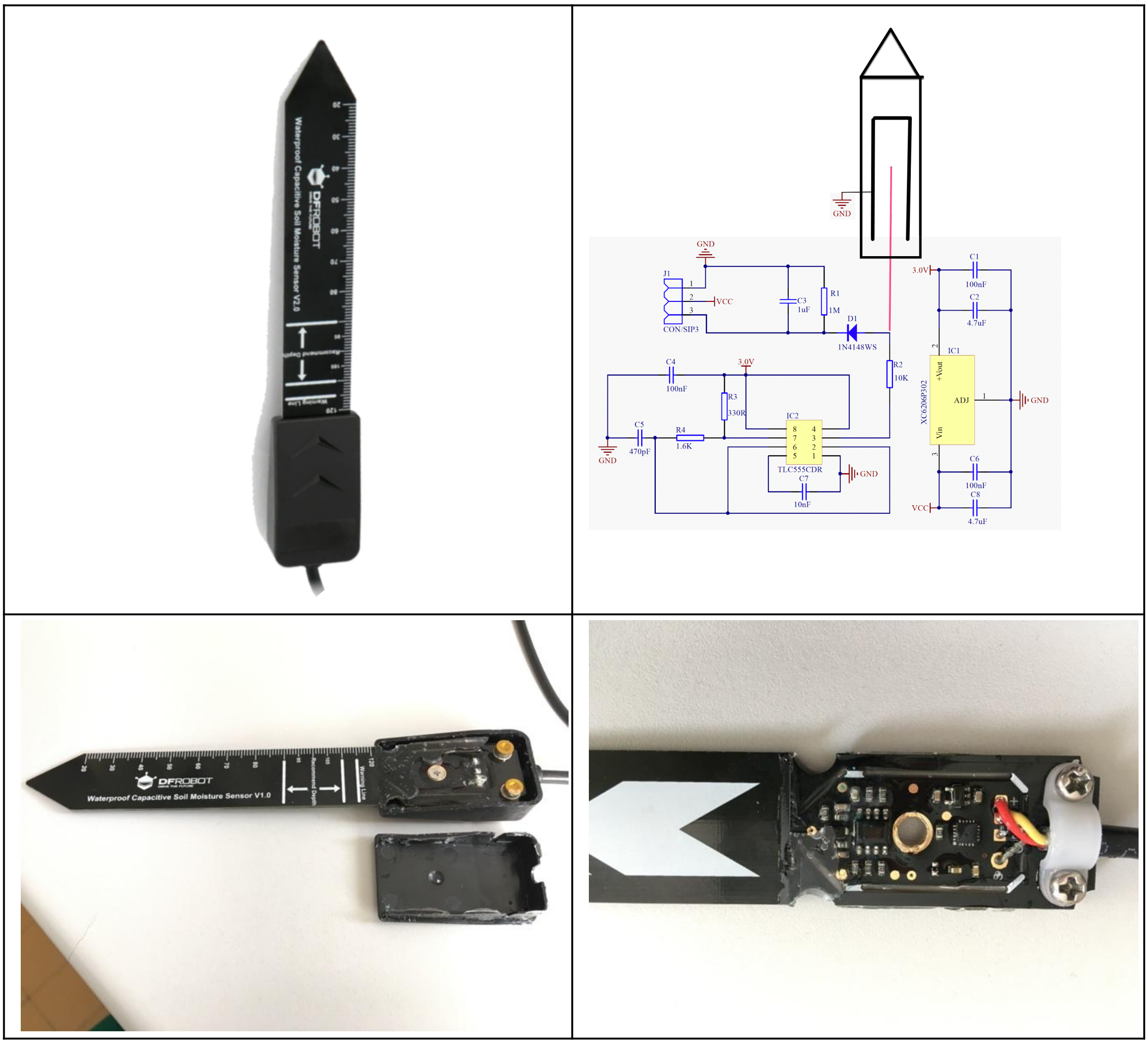


Figure 10. Views of the SEN0193, its connecting diagram (top) and electronic circuits (bottom).

4.2. Impact of the insertion depth

The depth to which the probe should be inserted in the soil is indicated on the probe itself. What is indicated is a range of insertion depths (minimum, maximum) and a warning line (i.e. this is the insertion depth which must not be exceeded).

As the range of insertion represents 2cm over a total length of 11cm, i.e. ~20% of the total length. Our objective was to test the impact on the signal (electrical tension) of various insertion depths in that recommended range.

The sensors were inserted in beakers filled with 4 water content (5 replicates for each treatment, i.e. each depth and each water content). Three insertion depths were tested:
- minimum: the line at 90mm
- maximum: the line at 110mm
- middle: in the middle of the 2 previous lines, at approximately 100mm.

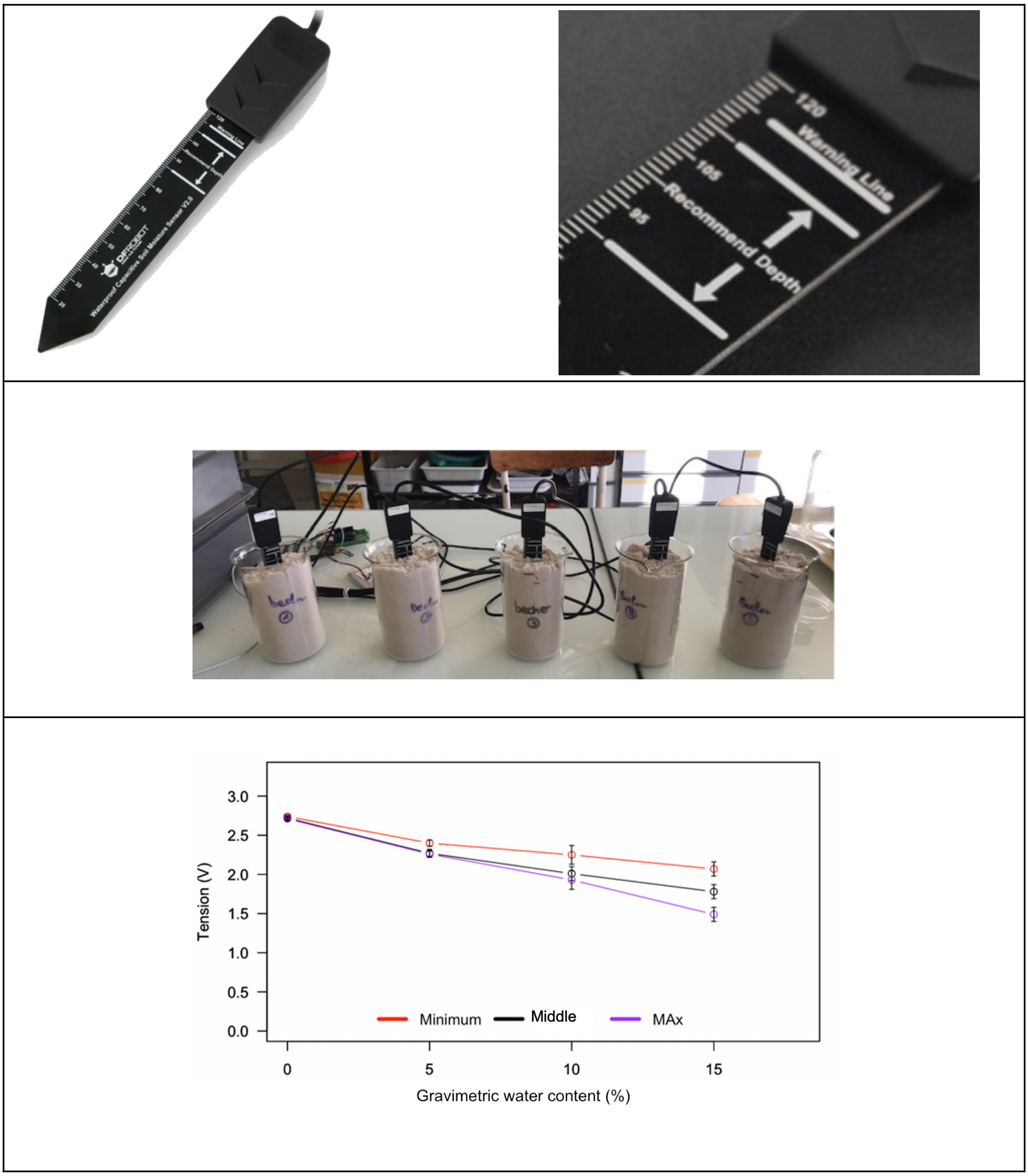


Figure 11. Top: view of the different recommended insertion depth. Middle: view of the experiment made to test the impact of insertion depth. Bottom: the output signal (tension in V) for different gravimetric water content and different insertion depth.

Our results show that the insertion depth influences the signal: the deeper the insertion, the steeper is the slope presenting the relation between insertion depth and signal. This shows that increasing the plate length below soil surface, increases the capacitive effect, and the sensitivity to water content. Consequently, increasing the insertion depth should make it possible to detect more accurately the differences between 2 water contents.

Indeed, our figure shows also that despite similar insertion depth, we obtain different signals when inserted at different, what could be wrongly interpreted as different water content.

Consequently, the calculation of the water content has to take into account the insertion depth.

In all the experiments presented in this report, the sensors were consequently inserted until the maximum recommended depth.

4.3. Soil temperature

According to the theory of capacitive measurements (presented in a previous section), the signal should be impacted by the soil temperature. Our objective was to measure this impact in a range of temperature that can be observed in field conditions, i.e. 10 to 40°C.

A set of 5 sensors were put in a single basin of wet soil (15% gravimetric content) that was covered by a plastic sheet to avoid evaporation in order to keep the water content constant. As the water content remains constant, the only factor that can impact the sensor's signal is the temperature and its changes.

To keep the water content as constant as possible the surface of the bucket was sealed with plastic sheets and it was sealed again above the probes and then put in the oven. The temperature was set at 10, 20, 30 and 40°C as presented in the figure below.

Figure 12. Left: a view of the 5 sensors and the temperature probe inserted in the soil (quartz sand) and the soil surface is sealed with plastic sheet to avoid evaporation and thus water content changes. **Right**: when put in the oven a second layer of plastic sheet was added on the top of the probes.

The figures below show that the signal was not significantly impacted when the soil temperature was increased from 20 to 30 to 40°C. When the temperature was brought back to 20°C, there has been a problem with the battery supplying power to the microcontrollers and the sensors and no signal was recorded during that period of time. When the power came back the temperature was decreased to 10°C which was associated with 2 characteristics:

- a significant but small (0.10 to 0.20V) decrease in the signal,

A change in the order of the signal provided by the sensors: when sensor 4 (purple) had the highest tension and sensor 2 (green) had the lowest, after the power was brought back and temperature decreased to 10°C the sensor 4 had the lowest value and sensor 2 the highest.

No explanation could be provided and complementary experiments are necessary to measure separately the impact of power interruption and of temperature decrease. This was not yet investigated because temperatures as low as 10°C are rare and during subsequent monitoring cuts in electrical supply could happen by accident, providing the information we need, without specific experiment.

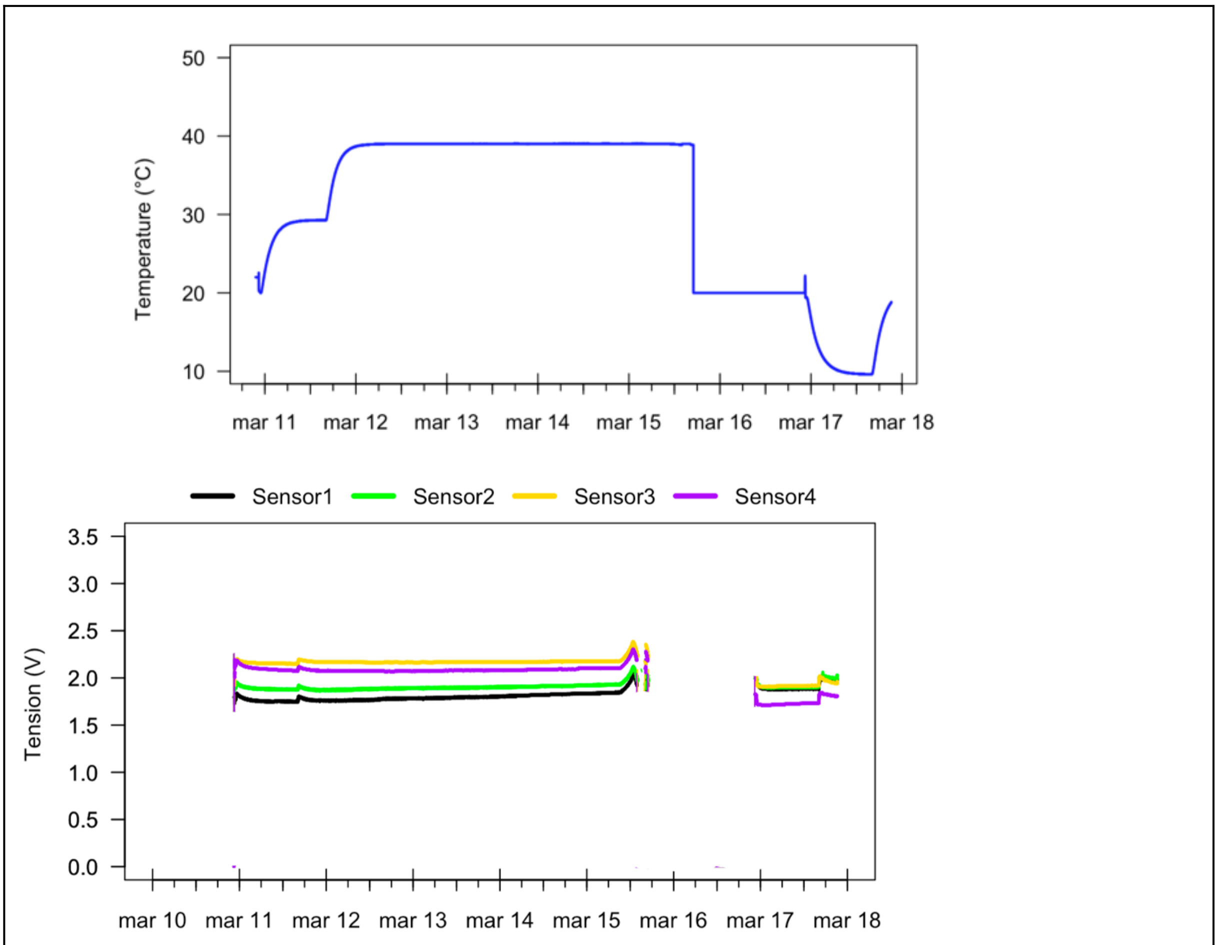


Figure 13. Top: sand temperature monitoring when the bucket was put in the over. Bottom: output tension monitoring when the bucket was put in the oven. The absence of monitoring from 15 to 16 March corresponds to a power failure while the oven temperature was maintained at 20°C.

The next figure presents the same data but highlights specific moments of temperature (fine blue line) changes. The temperature was recorded in the sand and is thus changing more slowly compared to the oven, due to the soil buffer effect. The signal recorded by the different sensors are the thick coloured lines (note that sensor 2 in red was out of order and was not plotted). These changes were small (<0.10V, see figure above) but occurred for each change of temperature. In the conditions of our experiment, we are sure that the water content was perfectly stable (as the bucket was double sealed with plastic) but in the field, such changes in the signal could be wrongly interpreted as changes in water content.

As DFRobot claimed that the electronic circuit was improved, one possible explanation of these short time peaks and the steady state (coming back to the original value of the system) is the existence of a system able to compensate for the signal from the temperature changes. DFRobot will be contacted and if no satisfactory answer is provided, more investigations will be conducted in the laboratory.

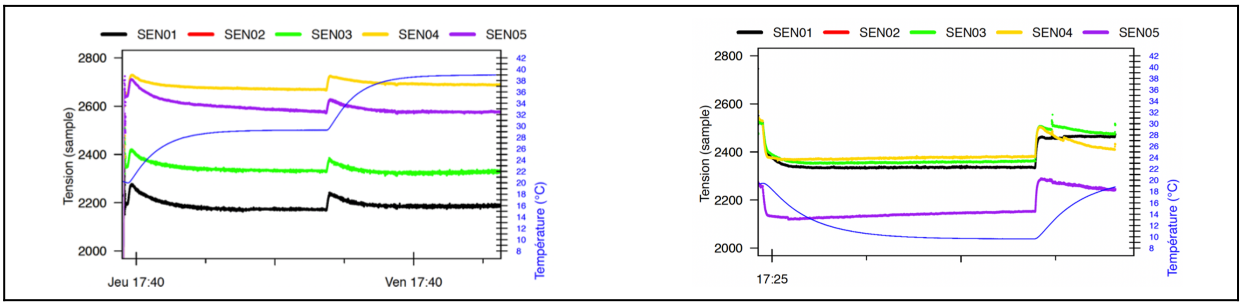


Figure 14. Focus on moments when the temperature (blue fine line) was changed

4.4. Heating of the electronics

A surprising change in the signal when water content was unchanged was observed by accident. The probes were left on the laboratory bench for several days (see figures below) and the water of 0% was consequently extremely stable. Despite this water content stability, a change in the signal was observed every at the same time. As the temperature probe was also left on the laboratory bench, we observed a temperature increase from 18°C to 25°C. This increase was indeed observed when the sunlight came through the window on the bench.

We made the hypothesis that the sunlight on the black box at the top of the sensors that contain all the electronic devices, could have induced changes in the electrical characteristics and in the signal. This hypothesis has to be confirmed because it is not consistent with the measure made in the oven: in the oven, the electronic part of the sensors were also subjected to temperatures up to 40°C without any impact on signal. Another experiment will be conducted to test the impact of sunlight and on the electronic circuit; meanwhile it would be a good practice to protect the sensor from direct sunlight.

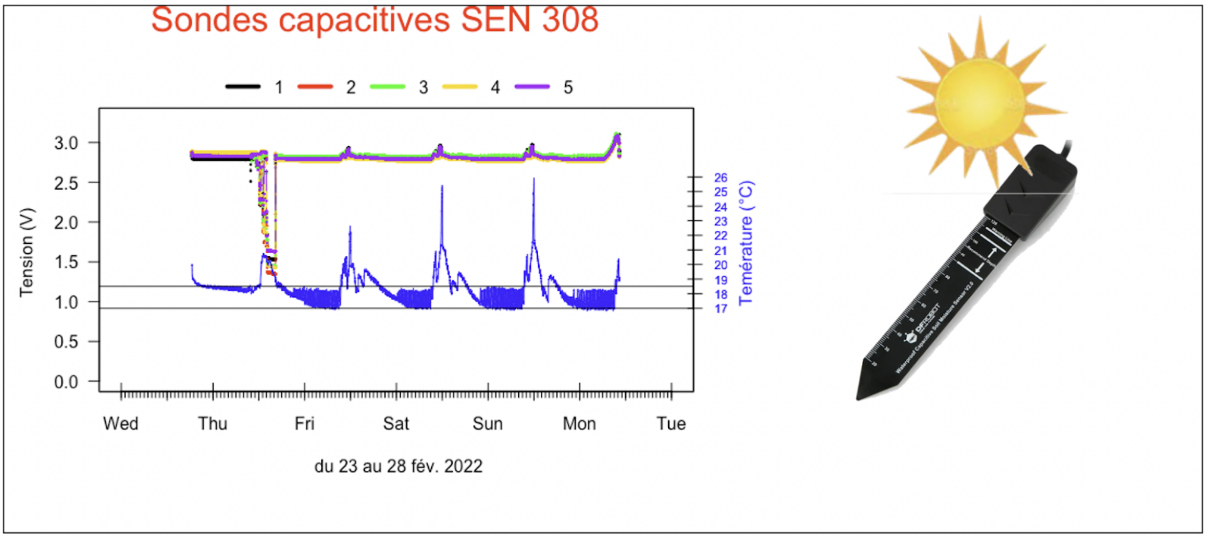


Figure 15. Temperature monitoring for the 5 sensors left on the laboratory bench after the experiment conducted on Thursday.

4.5. Testing the sensors' calibration

In order to check the claim of the company that SEN0308 had higher performances than its predecessor SEN0193, the following experiments were conducted using these 2 models. Such a comparison is particularly important because, compared to SEN0193, the price of SEN0308 is 4 higher and thus performance increase must be significant and relevant in the context of INTEL-IRRIS.

The capacitive sensors have to be calibrated by measuring the tension in the air (0% of water) and in the water (100% of water). As these 2 measures determine all the other results, we prepared a set of laboratory experiments to measure the impact of different factors on this calibration process:

(i) sensor calibration in water (100% volumetric water content): to test the impact of water quality on the sensor's signal, measurements were made in distilled water (no element in solution) and in a saline solution (using NaCl). This test seemed necessary as sensors can be installed in situations where the irrigation water can be saline and farmers could use saline water to make the calibration.

(ii) sensor calibration in the air (0% volumetric water content) vs dry sand: before each set of measurement, we systematically made a calibration in the air to check the stability of the results along time but we also wanted to see the impact on the signal with the mineral matrix. Thus, we measured the signal obtained from a sand that was oven dried (105°C during 48 h).

(iii) impact of removing the probe or slightly changing the soil structure. Changes in the way the solid particles are organised along the sensor can impact the signal. Such changes can occur when removing and re-inserting sensors in the soil, an operation that farmers will perhaps have to do during the growing period of their plants. Thus we made conducted a set of experiments for which, firstly the sensors were taken out and put back in the sand and secondly (5 times successively), the secondly the sand was removed from the beaker, put back in the soil and the probe reinserted (5 times successively).

The protocol was as follow:

- 2 to 5 min recording in the air with a measure every 20s

- 2 to 5 min recording in the water or in the dry soil (depending on the experiment)

- 2 to 5 min recording in the wet soil

and 5 successive similar cycles were conducted to have 5 replicates on which statistical analysis was possible.

Figure 16. Left: calibration of the sensors in water (100% water on a volumetric reference). Right: monitoring sensors tension when inserted in wet sand

When the output voltage indicated by DFRobot is 0 ~ 3.0VDC and 0 ~ 2.9VDC for the SEN0193 and 0308 respectively, the figure below (left side) shows:

- for SEN0193: a range of 1.3 ~ 2.5V approximately, much narrower than announced;

- for SEN0308: a range of 0.25 ~ 2.9V, close to the claim by the company. The maximum output voltage (2.9V) was actually fitting with the company claim but the minimum output voltage was higher: 0.25V for distilled water and 0.15V for saline water, both slightly different from 0V.

The error bars on the figure represent the standard deviation (sd) around the mean value obtained during the 5 replicates. In the air the sd is close to 0 explaining the absence of error bars, and in the water (distilled or saline) the sd remains so small that error bars are difficult to see. Such low uncertainty of the results make calibration in distilled and saline water significantly different, even if the difference remains low.

As a conclusion, this experiment:

- confirmed the higher sensitivity of the SEN0308 model compared to the previous SEN0193,

- showed the possible impact of using saline water when calibrating the probes.

The figure below (right side) also shows the comparison made between measures in the air and in dry sand, with and without reorganisation of the sand.

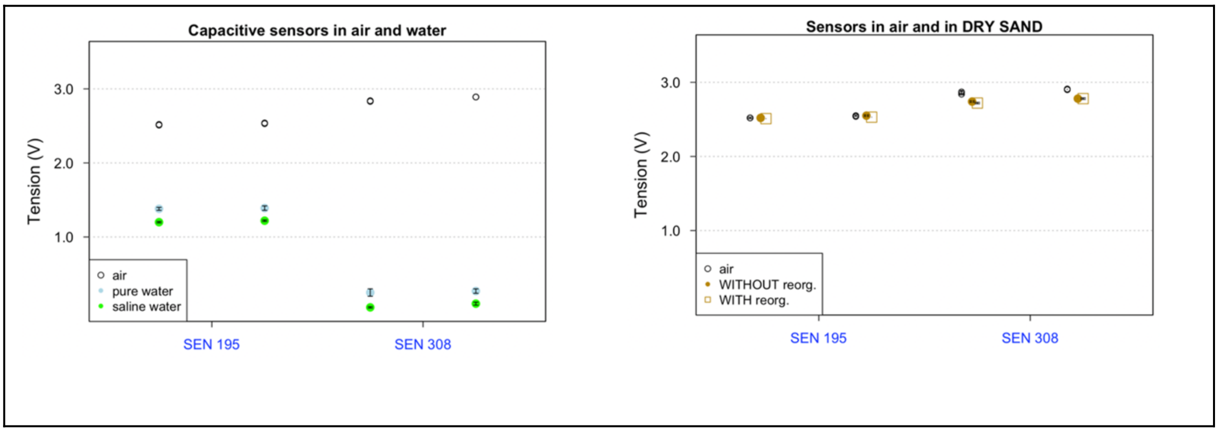


Figure 17. The hollow circles (O) correspond to measures made in the air, the coloured circles measures made in the wet sand (*i.e.* taking the sensor out and reinserting in the same beaker, without sand reorganisation), the hollow squares represent measures made in the dry sand after reorganisation (i.e. taking the sensor out, removing the sand, putting back the same sand in the same beaker and re-inserting the sensor). Finally, the colour of the symbols indicates the water quantity and quality: brown for dry sand, blue for sand wetted with distilled water and green for sand wetted with water containing salt.

For SEN0193: no difference was observed between air and sand.

For SEN0308:

+ a difference was observed between measures in air and dry sand but remained small (<0.10V). This difference was interpreted as the impact of the mineral particles of sand.

+ no difference was observed with or without sand reorganisation, which is consistent with the fact that in both cases the volumetric water content is 0%n whatever the organisation of sand grains around the probe.

4.6. Impact of water quality on wet sand

The sand was wetted to contain 15 % of water (g/g), with distilled water in a first set of experiments and with saline water in a second set. As in the previous section, the measures were made with and without soil re-organisation.

The tension measured in the air was exactly the same as in the previous experiment, indicating that this measure seems to be extremely stable. This value could be a way to detect (before installing the probes in the field) the probes that are out of order or the occurrence of problems somewhere in our data monitoring system.

+ distilled water

For the SEN0193 the range of tension between air (0% water) and wet sand (15% water) was narrow (<0.6V) which is consistent with the low sensitivity of this sensor model which was already mentioned. For the SEN0308 this range was much wider (>1.5V) and is also consistent with previous observation.

The difference between 'with' and 'without' reorganisation was low (>0.1V) for SEN0193 and much larger for SEN0308 (0.5V). We have not been able to provide an explanation for the large difference in the case of SEN0308; indeed we expected larger uncertainty due to random reorganisation of the wet sand (sometimes looser, sometimes more compact after reorganisation). But a systematic decrease in the signal (i.e. increase in volumetric water content) was unexpected. We can only observe that the signal decrease represented for both sensors around 15-20% of the 'dry-wet' range.

+ saline water

Using saline water impacted the signal: a lower tension was measured for both sensors. A tension decrease when the soil solution is saline is consistent with the observations made by (Thompson et al., 2007).

This set of experiments was only a first test to measure the differences between the 2 models of capacitive sensors and also to test the feasibility of our protocols. We will set up a new set of measures, focusing only on SEN0308 and increasing the number of replicates (from 2 to 5) in order to conduct a statistical analysis of our results.

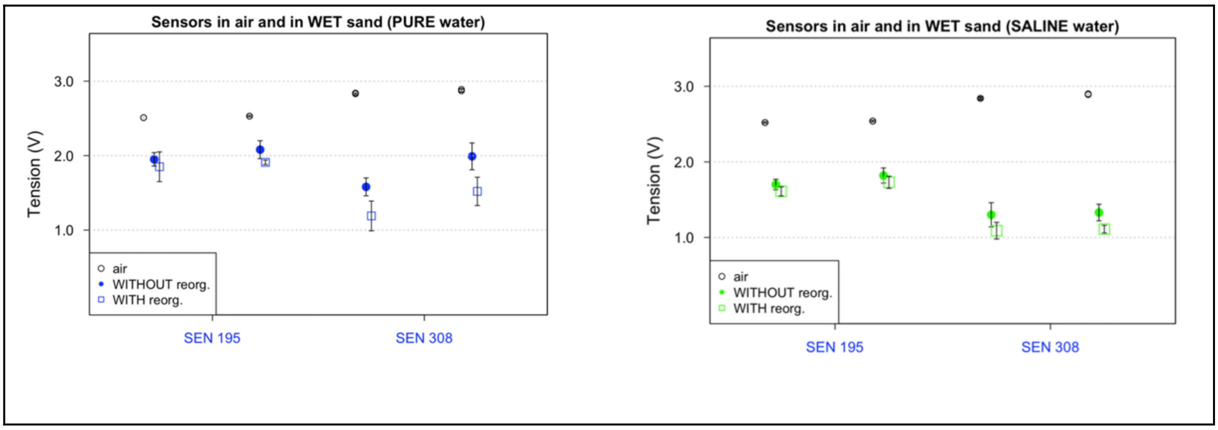


Figure 18. The hollow circles (O) correspond to measures made in the air, the coloured circles measures made in the wet sand (*i.e.* taking the sensor out and reinserting in the same beaker, without sand reorganisation), the hollow squares represent measures made in the wet sand after reorganisation (i.e. taking the sensor out, removing the sand, putting back the same sand in the same beaker and re-inserting the sensor). Finally, the colour of the symbol indicates the water quality: blue for distilled water and green for water containing salt. Error bars represent the standard deviation around the mean of the 5 replicates.

4.7. Capacitive measurements in a clayey soil

Your tests have been conducted on a pure sand in order to get a homogeneous material easy to manipulate. In order to illustrate the difficulties of working with clay material, an experiment was conducted using a clayey soil.

The soil was first dried and sieved at 2 mm, and poured in 5 beakers. The 5 probes were calibrated in the air, in the water and then in the dry clay. Then the dry clay was taken out of the beaker and mixed with 15 % of its weight with distilled water, put back in the beaker and the signal of the sensors were measured for 10 minutes. The soil was again taken, out mixed with additional water to reach 30 % of water and put back in the beaker. The same was done to reach 45, 60 and 75 % of water.

The main problem was that wet aggregates are sticky and plastic, meaning they are difficult to transfer from one container to another one, and when it is put back in the beaker, aggregates can easily be compacted and the soil structure can be significantly changed.

The figure below shows the output signal measured for clay (left side) and for sand (right side); note that the X axis do not have the same scales: 0 to 80 % of gravimetric water content for the clayey soil and 0 to 15 % for the sand material.

At 15% of gravimetric water content, the signal is quite similar in both experiments, when the 2 soils have different bulk density and different volumetric water content. This probably comes from the fact that the uncertainty of the clay material is quite large and the difference cannot be detected, even if it probably existed. This highlights the fact that for the next experiments we will need to precisely record the volume of the soil in the beaker to calculate as precisely as possible the bulk density and thus the volumetric water content.

It is noteworthy that at 60 and 75 % of gravimetric water, the signal is close to 0V indicating that the clayey material is already saturated, i.e. 100% volumetric water content (cm^3/cm3 soil).

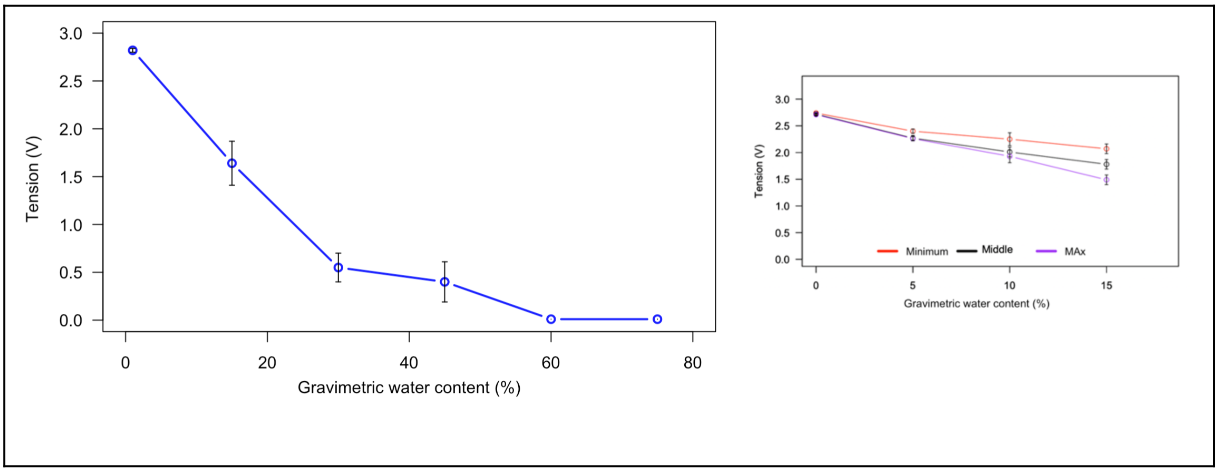


Figure 19. Left: output tension measured by the SEN0308 at content of distilled water ranging from 0 to 75 % (g water/g soil). **Right**: as a reminder, the output tension measured on a pure sand which gravimetric water content was ranging 0 to 15 %

Additional experiments will be conducted using different clay content to find a clayey soil that is easy enough to handle to make a relevant calibration and then test the impact of saline solution that can be different in clayey soils compared to sandy soils.

4.8. Power delivered by the batteries

When making experiments in a laboratory, the power is provided by the electrical plugs and a converter, ensuring constant power supply. This is not always the case in the fields where batteries have sometimes to be used. Thus, we also tested the impact of the supply voltage on the signal (output voltage) for dry and wet conditions.

We observed supply voltage sensors <= 3V have a significant impact on the output signal. Sensor is unusable below 2.6V.

Consequently, using a set of 2 x 1.5V batteries is a risky option as the batteries power could decrease fast, resulting in incorrect signal and thus incorrect interpretation about soil water content.

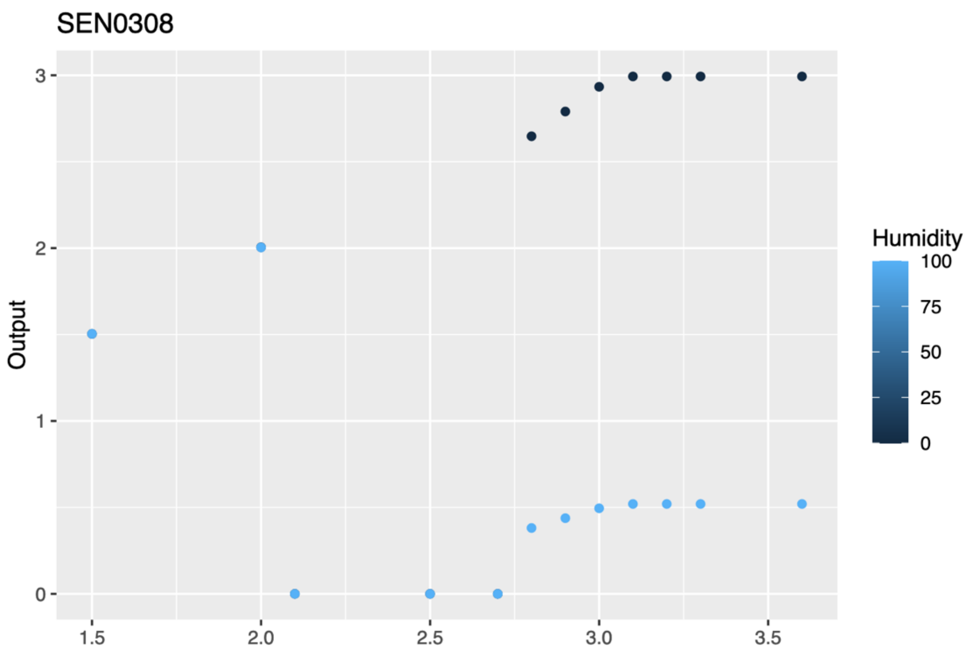


Figure 20. influence of supply voltage (V) on output voltage (V)

5. Recommendations for installing SEN0308 in the field

Not to forget to make calibration in air and in non saline water (if possible).

To get accurate calibration values, we recommend to record the value in the air for 2 to 5 minutes, then the value in the water for 5 minutes and do these 2 operations 5 times successively. Increasing the number of calibration points will allow us to check the precision of the probe that will be used (i.e. giving the same value when measuring the same thing).

Insertion: the probes needed to be gently inserted to avoid changing the soil structure. Gentle insertion will be difficult in many cases, for example:

- Stony profile
- Dry clayey soils which can be very hard and probe insertion can create cracks,
- Wet clayey soils that can stick on the probe, creating compacted volume around the probe.
- Dry sandy soil that can be hardened by the presence of a small amount of clay. Such soils are sometimes so hard that it is possible to break the sensor.

In case of soils too dry, it is possible to water the soil before the probe insertion.

In case of soils that harden when drying, it can be necessary to insert the probes sometime before the monitoring period.

If the farmers have to take the sensor out during the irrigation period, they must put the sensor back in the same hole if possible with limited disturbances, otherwise it must be inserted in a nearby position where the water content should be similar to the water content of the original position. Anyway, in case the sensor has been moved or even removed, the farmers must inform the project.

As the output signal is sensitive to the insertion depth, we recommend using the deeper insertion. INTEL-IRRIS should build a ‘stopper’ that could be installed on the top of the SEN038 so that the probe cannot be inserted deeper than the maximum recommended depth. Doing like this would guarantee that all.

At the moment our observation indicates that the output signal could be affected by direct sunlight heating the upper part of the sensor where the electronic circuit is located. Consequently, as long as we have no more information about this problem, it is safer to protect the upper part of the sensors from direct sunlight.

To manage irrigation, water content is generally recorded at 2 depths: at the root level, below the root level. The upper sensor monitors the amount of water that is accessible for the plant and thus controls the plant biomass. The deeper sensor is used to detect infiltration of water to deeper layers where the water is not accessible to the plant. This deeper sensor sends a warning signal indicating that water could be wasted.

Our suggestion is to use the SEND0308 where the roots are located and at the same time to install a SEN0193 below the rooting depth. This sensor which cost is very low (< 5 euros) is enough to send a signal indicating deep (and useless) water drainage. But this sensor is not waterproof, and we need to find a way to waterproof the part where the electronic circuit is located.

Finally, for the first field test, we would like to suggest to select soils (i) without coarse elements, (ii) that are as homogenous as possible, (iii) that are non-saline, in order to get sensors' output signals that are as easy as possible to interpret and to feed models and algorithms able to make relevant recommendations to the farmers.

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