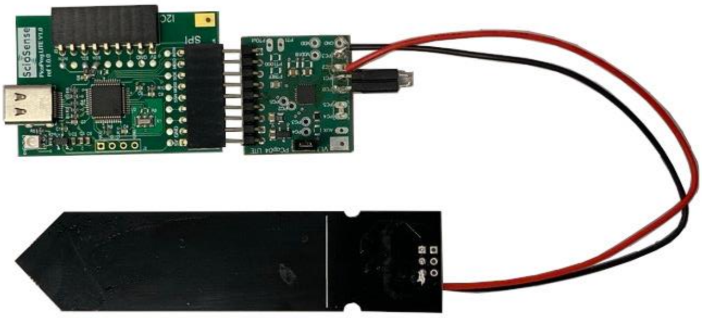


# Capacitive Soil Moisture Measurement with PCAP04 Evaluation Kit Application note

**Capacitive Soil Moisture Measurement with PCAP04 Evaluation Kit**

Version: 1.0

Release Date: 2025-22-12

Document Status: Production

# Table of Contents

# 1 Introduction

PCap04 is a capacitance-to-digital converter (CDC) with an integrated digital signal processor (DSP) for on-chip post-processing. It is based on the ScioSense PicoCap® principle and provides high speed, low power consumption, and high resolution. PCap04 supports a wide input capacitance range—from a few femtofarads up to several hundred nanofarads—across six measurement channels.
PCap04 supports multiple measurement topologies, including single-ended and differential sensors, in grounded or floating configurations. On-chip linearization and temperature compensation are available. Measurement results can be read out via digital interfaces (SPI/I²C) or via analog outputs (PDM/PWM), depending on the selected firmware/profile.

Accurate knowledge of soil water content is a key enabler for smart irrigation and precision agriculture. This application note describes how to measure soil moisture using the PCap04 Development Kit together with a two-electrode capacitive soil moisture probe. Soil water content is estimated by tracking the capacitance change of the probe as the dielectric permittivity of the surrounding soil changes.
For a general description of the Development Kit setup and software operation, refer to the PCap04 Development Kit User Guide and the PCap04 Datasheet, available on the product page:

https://www.sciosense.com/wp-content/uploads/2023/12/PCAP04-Development-Kit-User-Guide.pdf
https://www.sciosense.com/pcap04-capacitance-to-digital-converter/

# 2 Soil Moisture Measurement Principles

Two common approaches are used to determine soil water content: (1) direct methods (gravimetric/volumetric reference measurements) and (2) indirect methods based on a measurable soil property (e.g., electrical permittivity).

## 2.1 Direct Measurement Method

Direct methods quantify the actual water content of a soil sample. As a reference step, the sample is dried to remove free water. A common laboratory procedure is oven drying for approximately 24 h at 100–110 °C until the mass is stable.
After drying, water content can be calculated using either gravimetric water content (GWC) or volumetric water content (VWC). GWC is based on mass measurements of the wet and dry sample:

$$\theta_g = \frac{\mathrm{M_w}}{\mathrm{M_s}}$$

$M_w$: *mass of water content.*
$M_s$ : *mass of soil content.*

Volumetric water content (VWC) expresses water content per unit volume of soil. It can be computed from the sample volume and the equivalent water volume:

$$\theta_v = \frac{V_w}{V_s}$$

$V_w$ : *volumetric water content*
$V_s$ : *volumetric soil content*

In practice, VWC is often derived from gravimetric water content using soil bulk density ($\rho_b$) and water density ($\rho_w$):

$$\theta_v = \frac{\frac{m_{water}}{\rho_{water}}}{m_{soil}/\rho_{\mathrm{soil}}}$$

Direct methods are time-consuming and do not capture rapid moisture changes in real time. However, they provide the most reliable laboratory reference and are therefore recommended for sensor calibration.

## 2.2 Indirect Measurement Method

Indirect methods estimate soil water content from an associated soil property, such as electrical permittivity, conductivity, or thermal behavior. In this note, a capacitive probe is used to sense permittivity changes and is read out by the PCap04 CDC. Figure 1 illustrates the basic system concept.

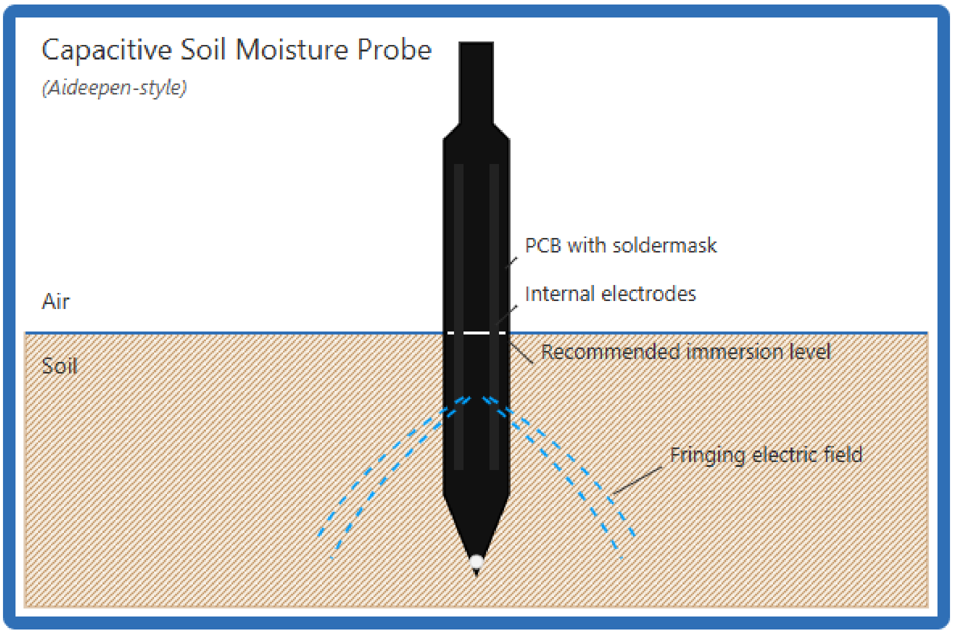



*Figure 1. Capacitive Soil Moisture Probe ( two-electrode)*

As shown in Figure 1, the probe is inserted into the soil. A change in soil permittivity changes the effective capacitance seen by the electrodes. The basic relation is: C = Q/V.

$$C = \frac{Q}{V}$$

For a fixed probe geometry, the capacitance can be approximated by: $C \approx \varepsilon_0 \cdot \varepsilon_{eff} \cdot G$, where ε0 is the vacuum permittivity, $\varepsilon_{eff}$ is the effective relative permittivity of the surrounding medium, and G is the geometry factor of the probe.

$$C \approx \varepsilon_0 \, \varepsilon_{eff} G$$

$\varepsilon_{eff}$ is the dielectric coefficient which changes by the water content of the soil so soil moisture sensor is sensitive to this change. Since ratio of the sensors are calculated based on this formula, it is seen that dielectric coefficient is the major factor for capacitance change so the sensor is reacting to this change once the water is poured into the soil as long as the geometry of the sensor is not changing.

# 3 PCAP04 Firmware Options

The software provides multiple configuration options and firmware profiles. The following sections summarize the Standard firmware (raw ratio readout) and the Linearized firmware (polynomial linearization and optional temperature compensation).

## 3.1 Standard Firmware

The Standard firmware outputs a normalized capacitance ratio between the selected measurement channel and the reference capacitor. It supports six single-ended measurements in grounded mode, or three channels in floating mode (paired pins). This mode is typically used for laboratory characterization and for verifying the measurement chain before calibration.

## 3.2 Linearized Firmware

The Linearized firmware applies polynomial linearization (typically up to third order) and optional temperature compensation (typically up to second order). It is intended for applications requiring a calibrated output derived from the raw capacitance ratio.
In the GUI, the Linearized firmware is available in pre-configured profiles (e.g., “Humidity” and “Pressure”). The profiles mainly differ in measurement rate and filter settings; both can be used for capacitive sensing applications, including soil moisture. Further information can be obtained from below link.

https://www.sciosense.com/wp-content/uploads/2023/12/PCap04-Application-Note-Linearization.pdf

# 4 Test Setup and Procedure

To achieve best accuracy, multiple calibration points should be recorded at different moisture levels. A gravimetric reference measurement is recommended for calibration. Prepare the soil by oven drying (e.g., 24 h at 105 °C) and allow it to cool to ambient temperature before measurements.

This note uses the Linearized firmware to map the raw capacitance ratio to a user-defined output (soil moisture). The required Development Kit components are shown in Figure 3.


*Figure 3 Elements of Development Kit*

Table 1 lists the ordering information for the PCap04 Development Kit and evaluation board.

*Table 1 Ordering Information*

| Sciosense Ordering Code | Part Number | Description |
|---|---|---|
| Pcap04-EVA-KIT V2.0 | 220300004 | PCap04 LITE board, PicoProg Lite, USB-C cable |
| PCap04 LITE V1.0 BGRP | 220300005 | PCap04 evaluation board |

Open the Evaluation Software with the Development Kit connected to the PC, click Verify Interface to confirm communication. Evaluation Software could be downloaded from below link.

https://downloads.sciosense.com/pcap04/

Once the evaluation software is opened, make sure that the Evaluation Software is connected to PC so please click **VERIFY INTERFACE** button on the screen. After successful verification, select the Linearized firmware profile (e.g., “Humidity”) to start the application firmware.

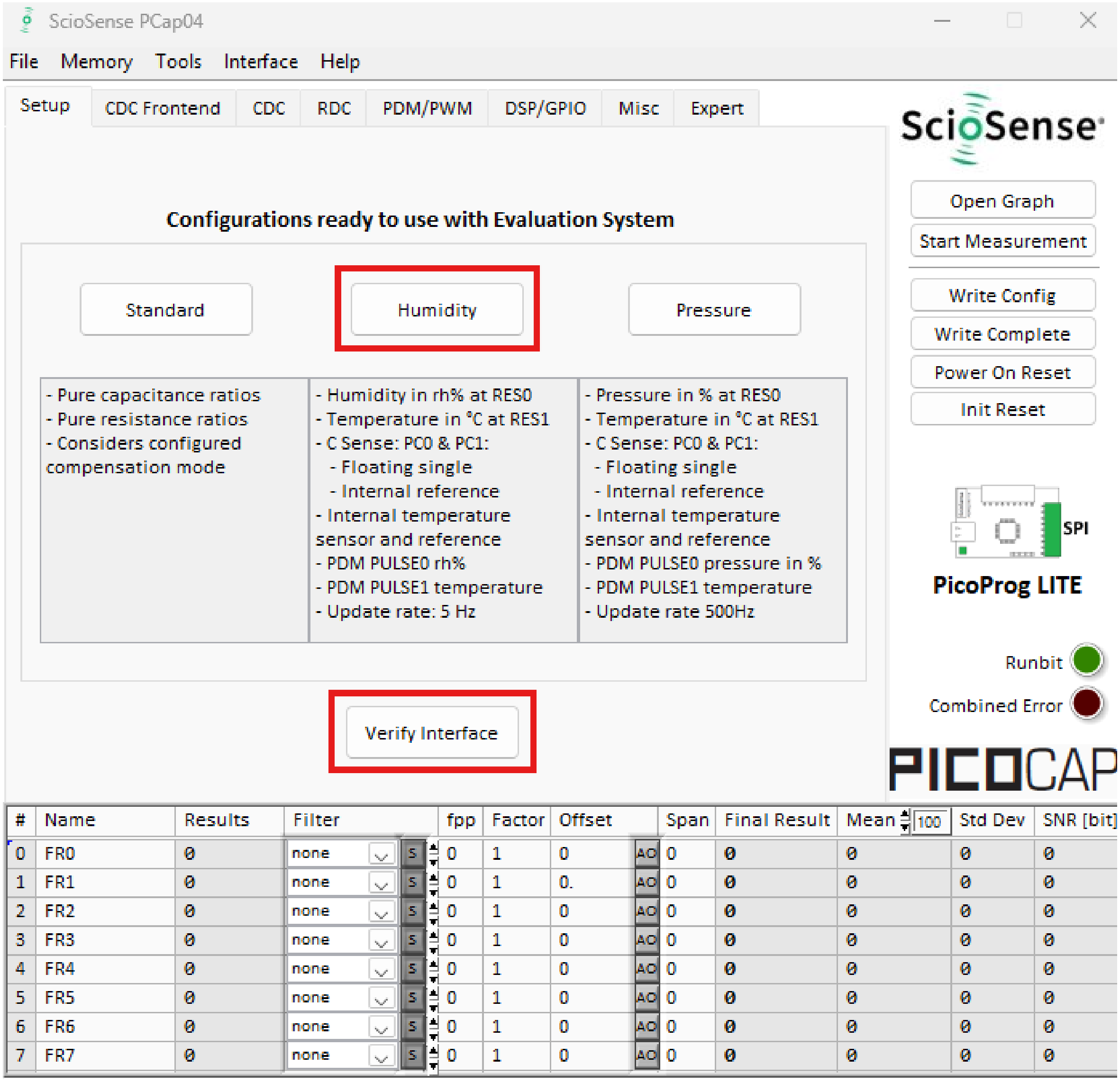



*Figure 4 PCAP04 Evaluations Software*

| # | Name |
|---|---|
| 0 | Humidity / %rH |
| 1 | theta / °C |
| 2 | ci_out |
| 3 | r_out |
| 4 | xi_out |
| 5 | yi_out |
| 6 | Pulse_Z |
| 7 | Pulse_theta |

*Figure 5 Output Parameters in the Linearized Firmware Profile*

The following GUI outputs are relevant for this application:

- Humidity (%rH): Final, calibrated output value. In this application, it represents soil moisture after calibration (the label remains unchanged in the firmware).
- Theta (°C): Linearized temperature result derived from the resistive measurement channel (RDC), if enabled.
- ci_out: Raw capacitance ratio used by the firmware (normalized ratio between measurement channel and reference).
- r_out: Raw resistance ratio for temperature measurement (Rmeas relative to Rref), if enabled.
- xi_out: Calibrated/normalized ci_out after two-point correction.
- yi_out: Calibrated/normalized r_out after two-point correction.
- Pulse_Z: Linearized Z output for the pulse interface.
- Pulse_theta: Linearized temperature output for the pulse interface.

Only ci_out (raw ratio) and Humidity (calibrated output) are required for the calibration procedure described in this note. Other parameters are not used and are therefore not discussed further.

The evaluation board provides six port pins (PC0…PC5). To improve noise immunity, a floating single-ended configuration is recommended for long leads and high-impedance probes. In this note, the Single Floating configuration is used.

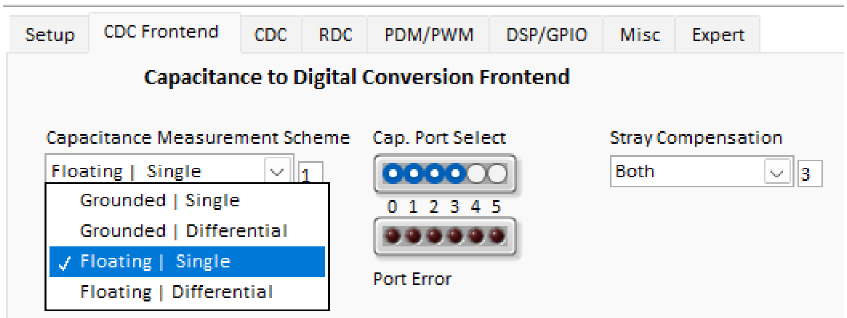



*Figure 6 Measurement Configuration: Single Floating*

For additional measurement schemes (grounded, differential, guard, etc.), refer to the PCap04 Datasheet.

In Single Floating mode, PC0/PC1 form capacitance channel C0 and PC2/PC3 form channel C1. Connect the external reference capacitor (Cref) to C0 (PC0–PC1). Connect the soil moisture probe to C1 (PC2–PC3).

An external reference capacitor is recommended because the internal reference range (0…31 pF) may be insufficient over the full moisture range. For this experiment, a 231 pF capacitor is used; adjust the value as required to avoid saturation across expected moisture levels.

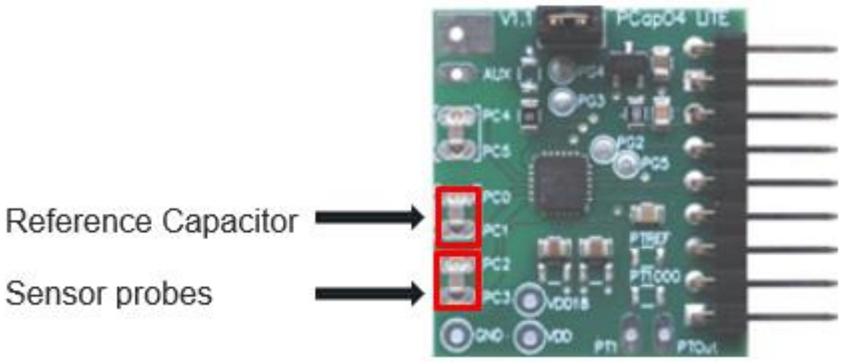



*Figure 7 Electrical Connections to the Evaluation Board*

In the GUI, select C1 as the capacitance channel used for linearization. This ensures the firmware uses the probe channel (C1) as the input to the polynomial mapping.

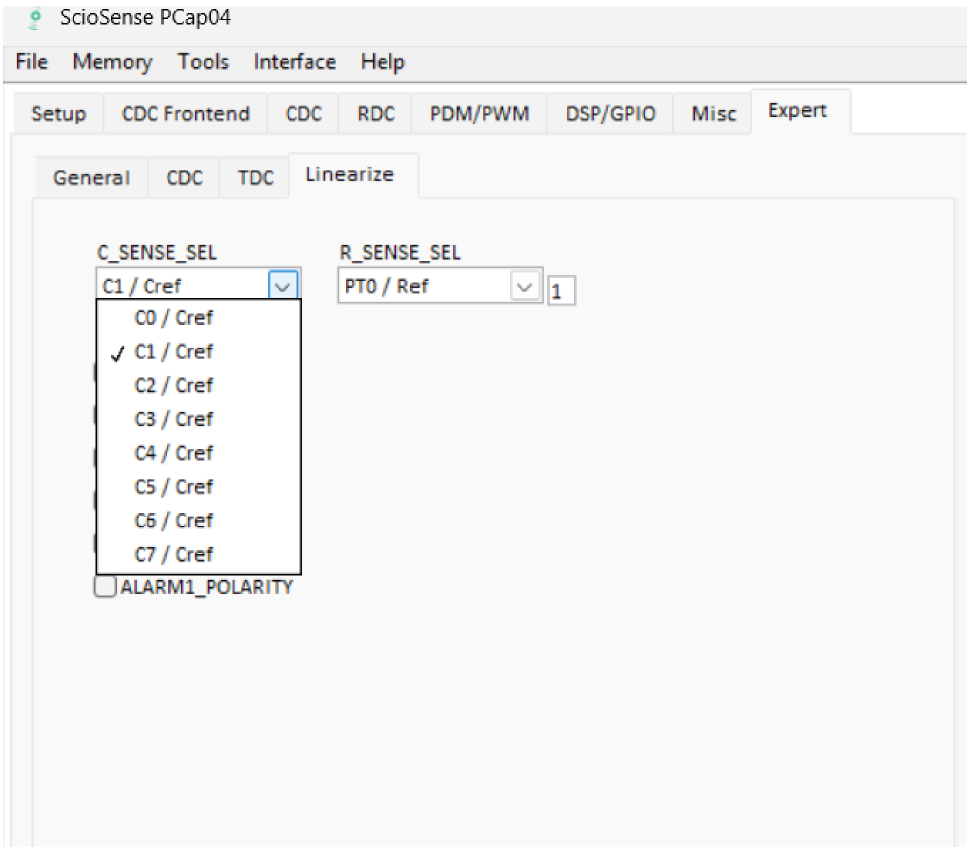



*Figure 8 Selecting the Linearized Sensor Channel (C1)*

After completing the hardware connections and GUI selection, the setup is ready for measurement. When the Linearized firmware is selected, it is automatically downloaded to the device.

## 4.1 Calibration Procedure

After the connections are made, start the calibration. Use fully dried soil (zero reference) as the first point. See Section 2 for details on sample preparation.
Insert the probe into the soil as shown in Figure 8. Keep insertion depth and probe orientation constant across all calibration points.

*Figure 9 Test Setup (Probe Inserted into Soil, Weight Scale and PCAP04 Evaluation Kit)*

Wait until the capacitance reading stabilizes before recording a point. Once ci_out is stable, open the Linearize section in the GUI.

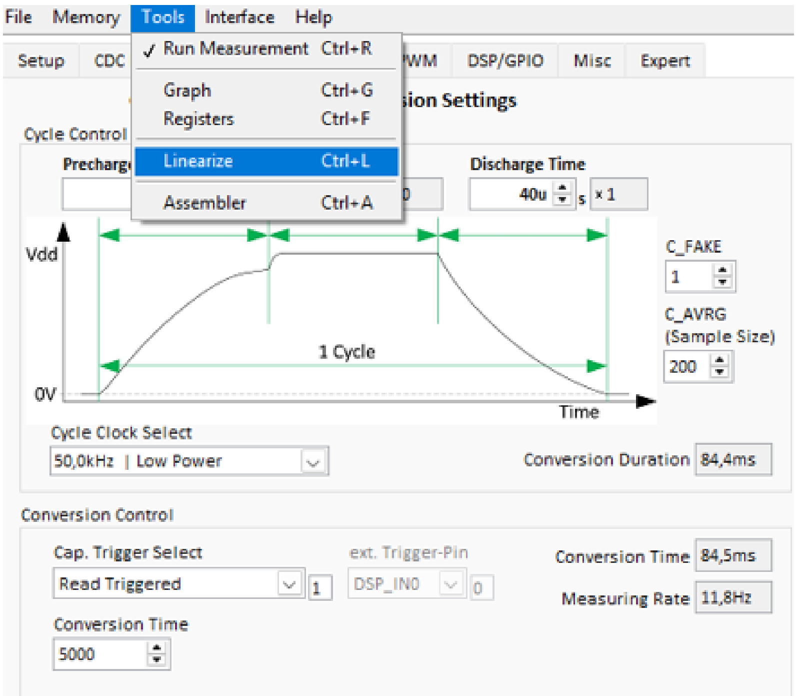



*Figure 10 Linearization Section*

The linearization dialog opens as shown in Figure 11.

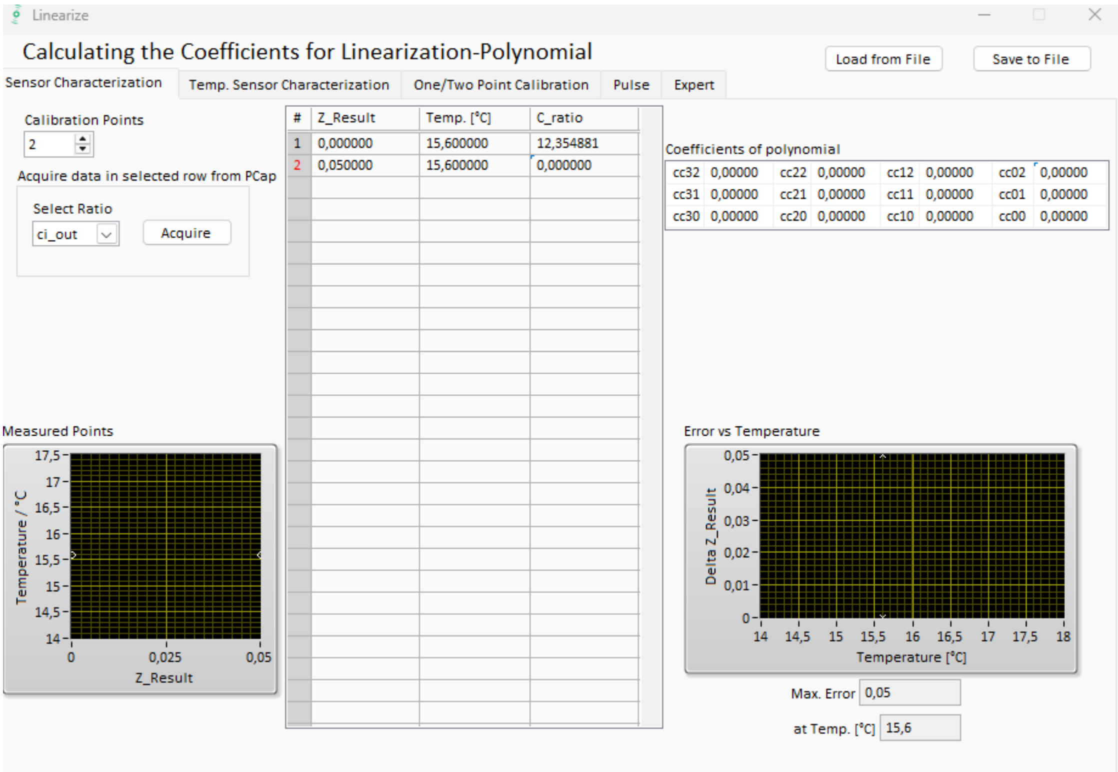



*Figure 11 Linearization  Table*

The number of calibration points can be set in the dialog. Increase the number of calibration points as needed for the desired moisture resolution.

The firmware supports calibration of multiple quantities (capacitance, resistance/temperature, and Z output). In this application, the temperature is kept constant; therefore, the default temperature value can be used for all points. However, at least **two-point temperature calibration** is **recommended** for real-life applications.

Starting from dry soil (0% moisture), add a known amount of water to the soil and mix thoroughly. The moisture level (by mass) is computed as:

$$Moisture\ Level\ (\%) = \frac{m_{water}}{M\_drysoil}\ x\ 100$$

After each water addition, allow the soil to equilibrate until the capacitance reading becomes stable. Depending on soil type and mixing, stabilization can take minutes to hours. Table 2 lists the moisture steps used in this experiment. For this experiment, moisture measurement between %0-20 with 4 steps is calculated as you can see below.

*Table 2 Moisture Levels Used for Calibration*

| Soil Content (g) | Water Content (g) | Moisture Level (%) | Step |
|---|---|---|---|
| 400 | 0 | 0 | 1 |
| 400 | 20 | 5 | 2 |
| 400 | 40 | 10 | 3 |
| 400 | 80 | 20 | 4 |

At very low moisture levels, the capacitance change per step can be small. Therefore, if moisture data below **5%** is required, it is recommended to include one or more additional calibration points below **5%** to improve accuracy. These steps could be increased depending on the desired accuracy.

For each step, once the reading is stable, record ci_out by clicking Acquire in the calibration table (Figure 12).

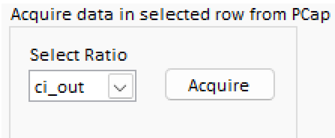



*Figure 12. Acquiring a calibration point*

After acquisition, the software calculates the capacitance ratio (C_ratio). Enter the corresponding Z_Result (target moisture level) for the recorded point. Use a consistent unit across all points (e.g., percent 0…100, or fraction 0…1).

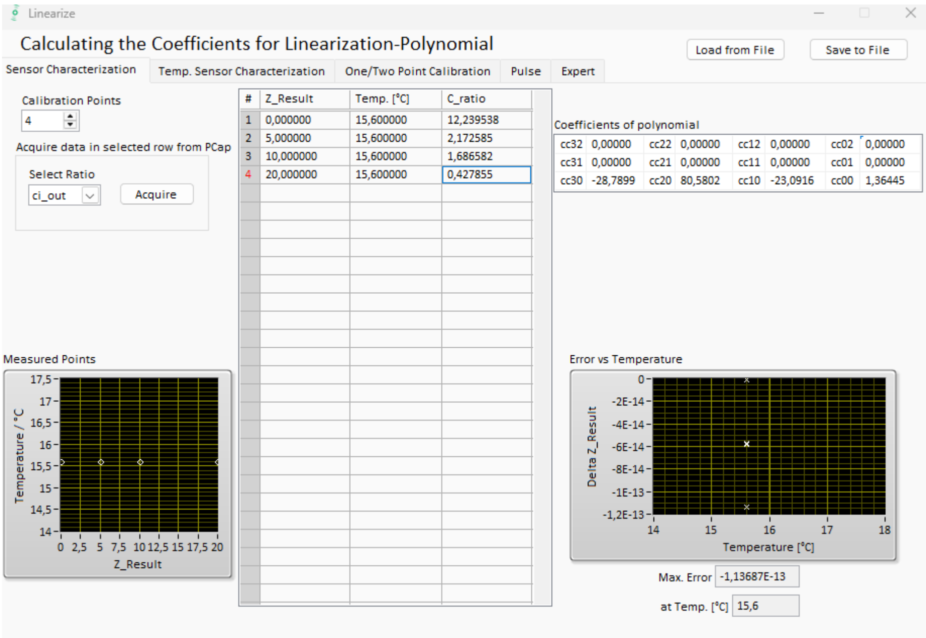



*Figure 13. Calibration Result Screen*

Immediately after adding water, the capacitance may increase sharply and fluctuate due to non-uniform water distribution, temporary conductivity changes, and air gaps around the electrodes. Mix thoroughly and allow sufficient settling time before recording the calibration point. In addition to that situation, it is possible to mix the water content and soil manually to accelerate the process of settling time.

*Important Notes*

- Although the primary cause of capacitance variation is the soil's dielectric properties, changes in the probe position can slightly alter the effective geometry and therefore the measured capacitance. For this reason, after mixing the soil and water, place the probe in the soil as consistently as possible (same location, depth, and orientation). This minimizes geometry-related variation.

- As it is mentioned in section 4, an external reference capacitor is recommended, as the internal reference range (0–31 pF) may not cover the full moisture range. Typical values are **100-300 pF**; the optimal value should be verified experimentally (in this setup, **231 pF** was used). If the reference capacitance is too small, the calculated output may saturate and the firmware may not be able to compute the target value. Since the device measures a ratio between the sensor capacitance and the reference capacitance, the reference value should be chosen as close as possible to the maximum sensor capacitance.

- If the sensor capacitance reaches the **nanofarad range**, the **discharge time** may become too long, which can lead to measurement errors (i.e., the sensor node may not fully discharge within the measurement cycle). In this case, use the **PCAUX pin** to provide an **external discharge path** by connecting an external resistor. A typical resistor range is **100 Ω to 1 kΩ** (select the value experimentally based on settling behavior and noise). After adding the resistor, ensure that the **PCAUX function is enabled** in the configuration.

Once all the calibrations steps are finished, results should be recorded to the calibration engine.

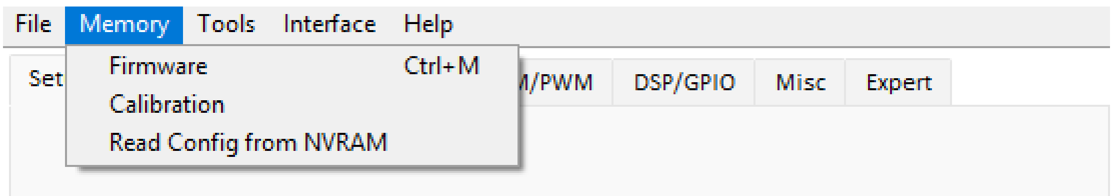
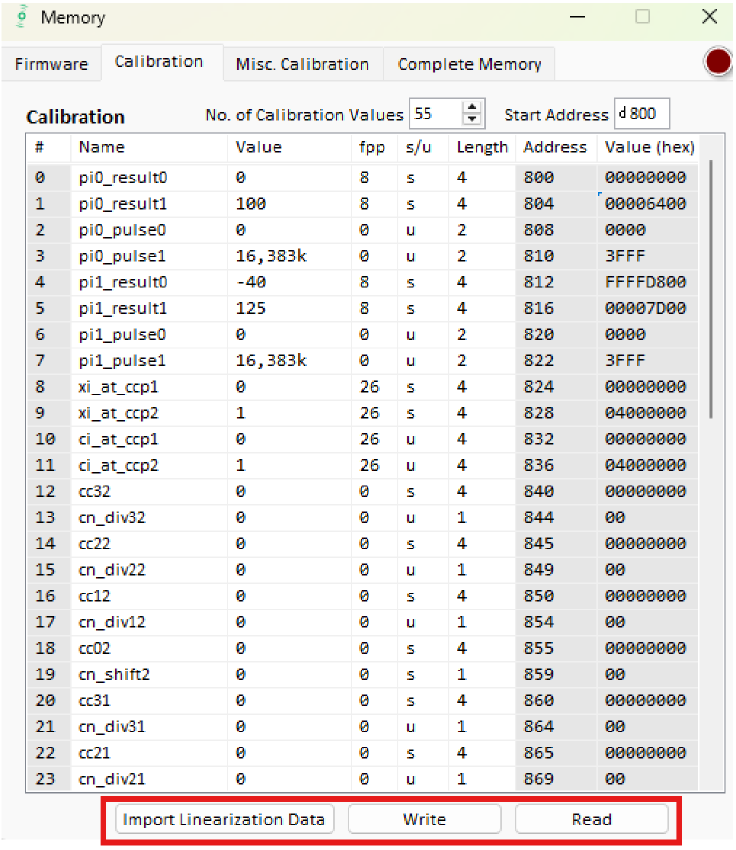



*Figure 13 Calibration Section*

In the **Calibration** section, click **Import Linearization Data** to load the linearization coefficients. Then click **Write** to store the parameters to memory. Finally, click **Read** to verify that the data has been written successfully.




| # | Name | Value | fpp | s/u | Length | Address | Value (hex) |
|---|---|---|---|---|---|---|---|
| 0 | pi0_result0 | 0 | 8 | s | 4 | 800 | 00000000 |
| 1 | pi0_result1 | 100 | 8 | s | 4 | 804 | 00006400 |
| 2 | pi0_pulse0 | 0 | 0 | u | 2 | 808 | 0000 |
| 3 | pi0_pulse1 | 16,383k | 0 | u | 2 | 810 | 3FFF |
| 4 | pi1_result0 | -40 | 8 | s | 4 | 812 | FFFFD800 |
| 5 | pi1_result1 | 125 | 8 | s | 4 | 816 | 00007D00 |
| 6 | pi1_pulse0 | 0 | 0 | u | 2 | 820 | 0000 |
| 7 | pi1_pulse1 | 16,383k | 0 | u | 2 | 822 | 3FFF |
| 8 | xi_at_ccp1 | 0 | 26 | s | 4 | 824 | 00000000 |
| 9 | xi_at_ccp2 | 1 | 26 | s | 4 | 828 | 04000000 |
| 10 | ci_at_ccp1 | 0 | 26 | u | 4 | 832 | 00000000 |
| 11 | ci_at_ccp2 | 1 | 26 | u | 4 | 836 | 04000000 |
| 12 | cc32 | 0 | 0 | s | 4 | 840 | 00000000 |
| 13 | cn_div32 | 0 | 0 | u | 1 | 844 | 00 |
| 14 | cc22 | 0 | 0 | s | 4 | 845 | 00000000 |
| 15 | cn_div22 | 0 | 0 | u | 1 | 849 | 00 |
| 16 | cc12 | 0 | 0 | s | 4 | 850 | 00000000 |
| 17 | cn_div12 | 0 | 0 | u | 1 | 854 | 00 |
| 18 | cc02 | 0 | 0 | s | 4 | 855 | 00000000 |
| 19 | cn_shift2 | 0 | 0 | s | 1 | 859 | 00 |
| 20 | cc31 | 0 | 0 | s | 4 | 860 | 00000000 |
| 21 | cn_div31 | 0 | 0 | u | 1 | 864 | 00 |
| 22 | cc21 | 0 | 0 | s | 4 | 865 | 00000000 |
| 23 | cn_div21 | 0 | 0 | u | 1 | 869 | 00 |

*Figure 14 Calibration Table*

Once calibration is complete, ensure that the configuration is stored by clicking **Write Config** and then **Write Complete** where is located in the main screen.

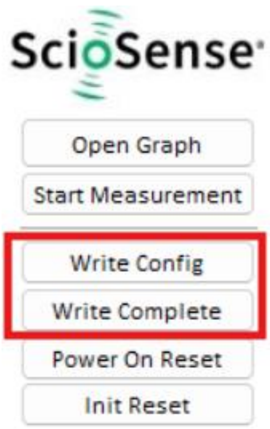



*Figure 15 Write Config and Write Complete*

Finally, calibrated value of humidity could be observed as below.

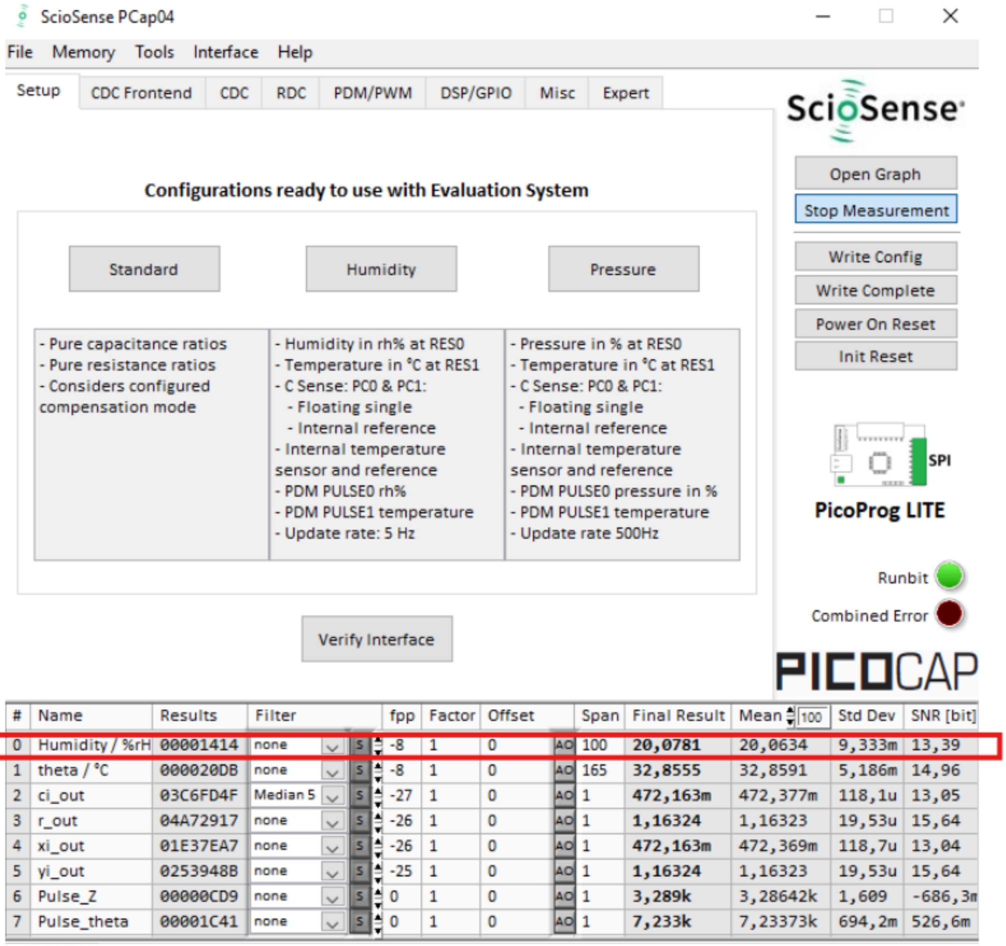



*Figure 16 Calibrated value of humidity*

# 5 RESULTS

After completing the calibration, moisture measurement steps has been repeated for same level of moisture. Here is the result for different samples of soils.

*Table 3 Measurement Results*

| Sample Number | Actual Moisture Level(%) | Measured Moisture Level (%) | Deviation (%) |
|---|---|---|---|
| 1 | 0 | 0,011 | 1,1 |
| 2 | 5 | 5,41 | 8 |
| 3 | 10 | 9,95 | 2,2 |
| 4 | 20 | 19 | 5 |

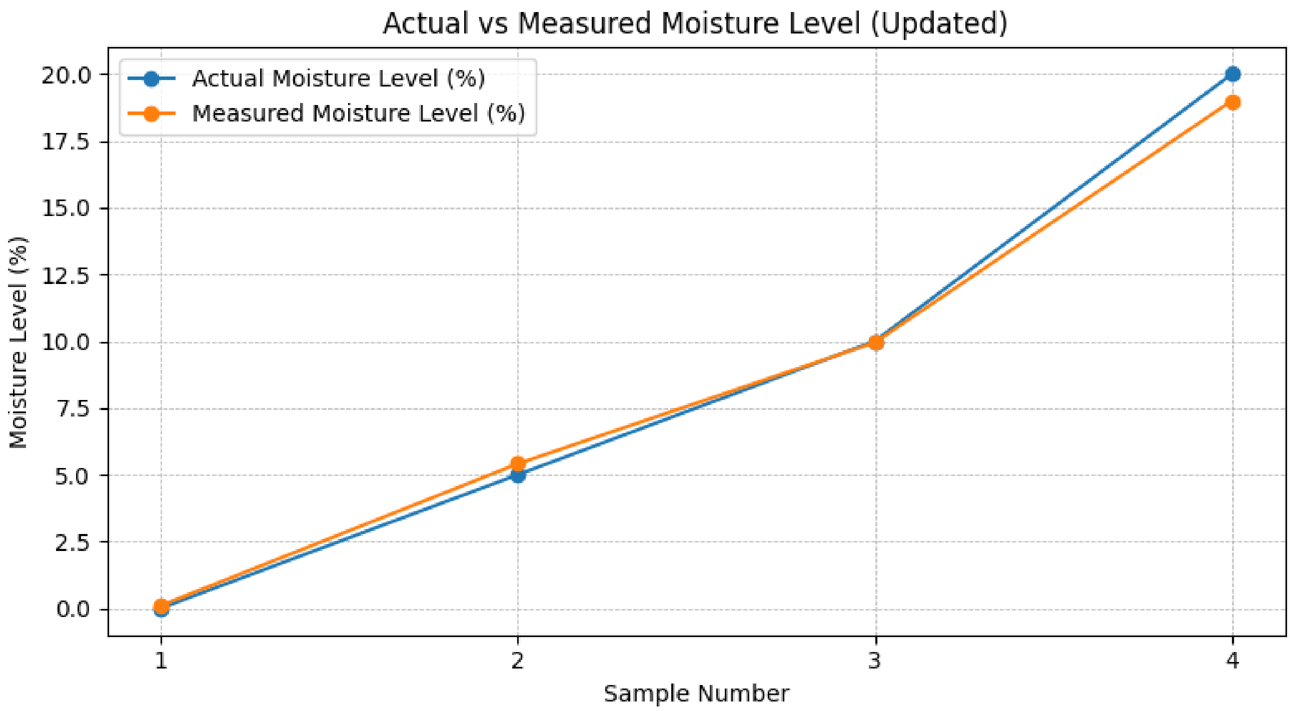



*Figure 16 Actual vs Measured Result Comparison*

As shown in the table 3, the sensitivity of the moisture measurement fluctuates at low moisture levels. Therefore, as also recommended in Section 4.1, additional calibration points can be applied in the low-moisture region, particularly between **0% and 5%** and between **5% and 10%** moisture. Since most plants require moisture levels above **10%**, additional low-moisture calibration steps are not included in this application note. In addition to that, test the sensor across different soil types. In this experiment, **sandy soil with low rock content** was used.

# 6 Sample Configuration

During this experiment, below configuration is used respectively from MSB to LSB. Registers could be changed via Evaluation Software Control Panel.

For further details about the registers, please check **PCAP04 datasheet.**

*Table 4 Configuration Registers*

| Registers | Settings |
|---|---|
| Register 3, 2, 1, 0 | 0x10F80019 |
| Register 7, 6, 5, 4 | 0xC80F0031 |
| Register 11, 10, 9, 8 | 0x00138800 |
| Register 15, 14, 13, 12 | 0x07FF0401 |
| Register 19, 18, 17, 16 | 0x00000000 |
| Register 23, 22, 21, 20 | 0x30500100 |
| Register 27, 26, 25, 24 | 0x07500473 |
| Register 31, 30, 29, 28 | 0x2982005A |
| Register 35, 34, 33, 32 | 0x40570029 |
| Register 39, 38, 37, 36 | 0x10000000 |
| Register 43, 42, 41, 40 | 0x000A0301 |
| Register 47, 46, 45, 44 | 0x01000000 |
| Register 51, 50, 49, 48 | 0x00000000 |

# 7 Conclusion

With this application, capacitive sensing principle is used to understand the behaviour of the soil moisture content. PCAP04 evaluation board is used together with capacitive soil sensor.

Due to the high measurement resolution of the PCAP04, an overall average deviation of **10%** was achieved in the moisture-content measurements under the tested conditions. The sensitivity and accuracy can be further improved by increasing the number of calibration points, particularly around the moisture range of interest.

It should be noted that the measurement quality also depends on the **effective sensor geometry** and probe placement. Repositioning the probe or inserting it into a different kind of the soil can change the fringing-field distribution, resulting in a different effective capacitance and therefore affecting the measurement accuracy.

Finally, perform the required calibration steps across the intended operating range, including at least a **two-point temperature calibration** and **multiple moisture calibration points**.

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# 9 Revision information

*Table 1: Revision history*

| Revision | Date | Comment | Page |
|---|---|---|---|
| 1.0 | 2026-01-30 | First version | All |

**Note(s) and/or Footnote(s):**

1. Page and figure numbers for the previous version may differ from page and figure numbers in the current revision.
2. Correction of typographical errors is not explicitly mentioned.

**Address:** Sciosense B.V.
High Tech Campus 10
5656 AE Eindhoven
The Netherlands

**Contact:** **www.sciosense.com**
**info@sciosense.com**