# Simple Soil Moisture Probe for Low-Cost Measurement Applications

**Article** · January 2005



**3 authors:**


Stefan Schlaeger
sceme.de GmbH



Christof Hübner
Mannheim University of Applied Sciences



Rolf Becker
Rhine-Waal University of Applied Sciences

# Simple Soil Moisture Probe for Low-Cost Measurement Applications

Stefan Schlaeger[1,2], Christof Huebner[1,3], Rolf Becker[1,4]
[1] Forschergruppe Feuchtemesstechnik, Soil Moisture Group (SMG), University of Karlsruhe, Germany
[2] SCHLAEGER – mathematical solutions, Karlsruhe, Germany
[3] University of Applied Sciences, Mannheim, Germany
[4] University of Karlsruhe, Germany

*ABSTRACT.* A simple and cost-effective soil moisture probe is described. It consists of a transmission line in the feedback loop of a ring oscillator, which can be embedded in soil or other material of interest. The water content of the surrounding material influences the frequency of the oscillator counted by a microcontroller circuit and transformed into water content by a calibration function. An integrated temperature measurement circuit may compensate for thermal effects and detect frozen material. The main challenge is a robust and low-cost probe design, especially suited for building sensor arrays to determine water content distribution in heterogeneous media.

*Keywords: simple soil moisture probe, ring oscillator, calibration procedure*

## 1 Introduction

For many applications soil moisture measurement devices like time domain reflectometers are too expensive and offer more features than really needed. Therefore a prototype for a simple and economical soil moisture probe has been developed, which allows measuring the mean moisture. Another important state variable besides moisture is temperature. Temperature measurements are needed for many purposes: To detect if the soil is frozen, which would change its hydraulic properties drastically. To gain information important for energy budget investigations (soil heat flux). A coupled moisture and temperature sensor could help to get more insight into the problem of temperature as tracer. Therefore a moisture sensor and a temperature sensor have been combined in one device. The probe is named *Simple Soil Moisture Probe* (SISOMOP). Its temperature senor is a common semiconductor bandgap temperature sensor. The soil moisture measuring part is based on a ring oscillator whose frequency is changing with water content. This principle has been known for many years and varied in several ways [1, 2]. Recent patents focus on the ability to compensate for some level of variable conductivity, e.g. by analyzing the waveform on the transmission line in detail [3, 4]. Though the measurement principle has already been investigated, there is still room to improve electronic design and develop application specific transmission lines.

## 2 Sensor Design

### 2.1 Ring Oscillator and Transmission Line

The core of the probe's moisture sensor is a ring oscillator based on a digital inverter, which acts like a line driver (Fig. 1). This inverter drives a transmission line the end of which is fed into its input again. This makes the line driver oscillate. If a logic 1 state travels along the transmission line it will reach the input where it is inverted. The output of the line driver becomes logic 0 and this distortion propagates along the transmission line, until it reaches the input of the inverting line driver. It is transformed into logic 1 and sent out again. The line driver toggles with a frequency determined by the propagation velocity of the positive and negative voltage pulses along the transmission line.

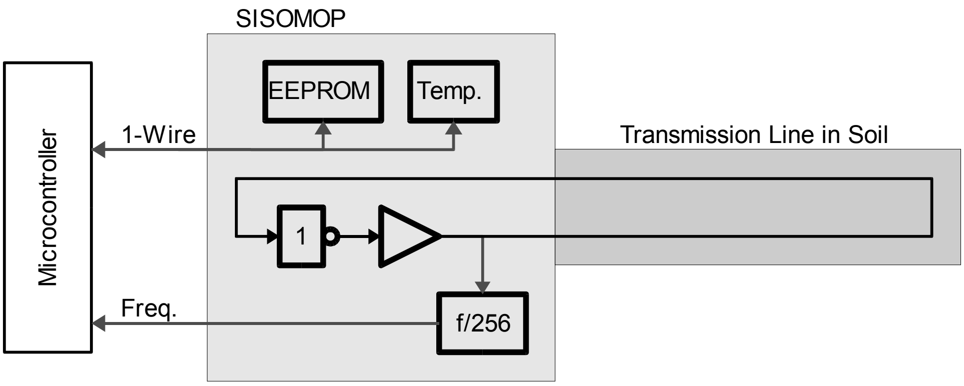


Fig. 1 Block diagram of the Simple Soil Moisture Probe and Temperature Sensor

If the transmission line is buried in soil, the pulse will interact with the surrounding medium, especially the stored water. The higher the moisture the higher the effective dielectric permittivity, leading to a lower wave propagation velocity $v_p$ and a thus lower frequency of the ring oscillator. The inverting line driver is realised in ECL logic. The transmission line consisting of two copper strips is etched on one side of a two-sided epoxy printed circuit board (PCB), which also carries the necessary electronic parts (Fig. 2 and Fig. 3). This leads to a simple, robust, and cost-effective design. To seal the strip line and to protect it from scratches when pushed into soil, the transmission line is covered by a protective lacquer.


Fig. 2 Printed circuit board of the Simple Soil Moisture Probe, size: 185 mm × 30 mm

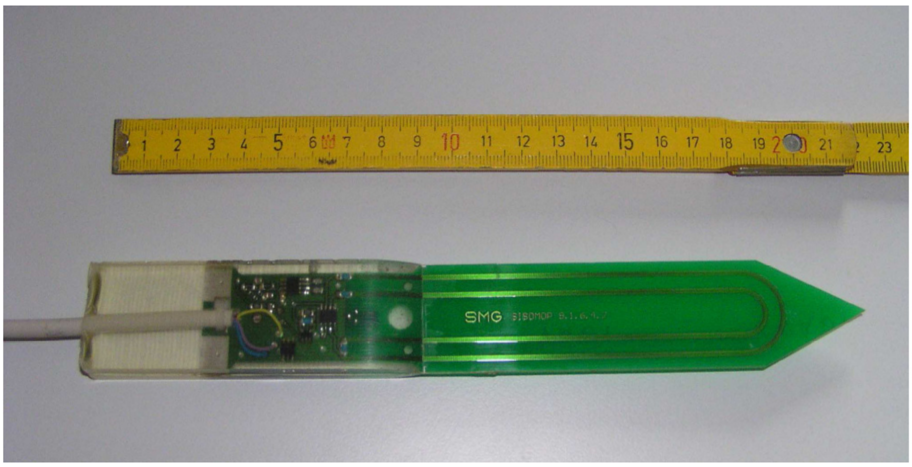

Fig. 3 Close-up picture of the Simple Soil Moisture Probe

The electrical field in the cross section of the PCB is shown in Fig. 4. It concentrates around the copper conductors only slightly shifted towards the upper side of the PCB where the conductors are positioned.

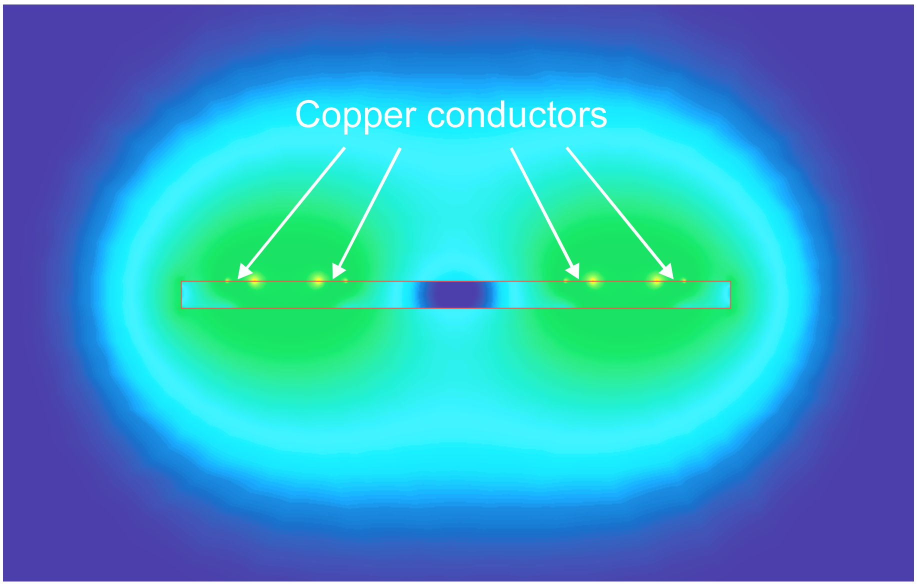


Fig. 4 Qualitative view of the electrical field distribution in the cross section of the PCB. The surrounding material is assumed to be air. Dark areas correspond to low electrical field strength and bright areas (between two copper conductors on the left and on the right hand side) to high electrical field strength.

The lancet formed by the PCB is rigid and flexible at the same time due to the glass fiber substrate. The width of the PCB is 3 cm and the length of the part forming the ring line can vary between 10 and 20 cm depending on the user's need. The electronics occupy additional 5 cm. The typical frequency range determined by the current ring line layout is around several hundred megahertz. This ring oscillator frequency is too high to be countable by a standard microcontroller. A frequency divider brings it down to a range which can be conveniently counted. To determine the frequency the microcontroller counts the signal transitions from logic 0 to 1 during a fixed predefined timing window. The resulting moisture counts $N_c$ are proportional to the oscillator frequency and thus for the propagation velocity of the electromagnetic wave along the transmission line.

## 2.2 Integrated Temperature Sensor

The chosen temperature sensor DS18B20 [5] is a digital thermometer with a so-called *1-Wire bus* interface. A microcontroller can communicate with the chip over this interface, which only needs one date line and ground to transfer the digital data. The DS18B20 measures temperatures between -55°C and 125°C with an accuracy of ±0.5°C from -10°C to 85°C without calibration or error correction. The maximum resolution of 12 bits corresponds to temperature steps of 0.0625°C. A very useful feature of this integrated circuit is a unique 48 bit identifier stored in its ROM. Thus the combined moisture and temperature sensor using this chip can be identified uniquely. This information can be used to refer to sensor specific external calibration data if needed.

## 3 Calibration and Experimental Results

### 3.1 Preliminary Investigations

The sensitive area of the SISOMOP which is described by the extension of the electrical field is very small (cf. Fig. 4). This means in return that the influence of different soil densities or probe insertion events is very high. To receive adequate counts $N_c$ at different moisture states for comparable soil situations and insertion events the calibration procedure was carried out during a dry-out experiment. The dimensions of the soil sample and the position of the moisture measurement device compared to the soil-air boundary have an influence how much the local moisture measurements represent the mean moisture of the probe. Fig. 5 describes the experimental setup for the determination of a minimal soil sample probe which is not influenced by any surrounded material. Using several different soil samples the minimum sensitive area was set to approximately 8 cm in diameter.

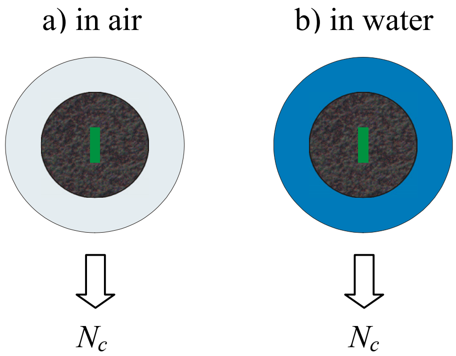


Fig. 5 Determination of minimum sensitive area around the SISOMOP using air- and water-surrounded soil samples

To get more independent information about the electrical properties (dielectric permittivity $\varepsilon$) of the soil a conventional time domain reflectometry (TDR) rod-probe has been inserted in the same soil sample. The two probes will be very close to each other so the interaction of the probes has also to be taken into account. Fig. 6 shows three different combinations of SISOMOP and/or TDR-probe inside of one soil sample. Similar to the procedure from Fig. 5 the minimum distance between these two measurement devices has been determined for several soil samples by at least 10 cm.

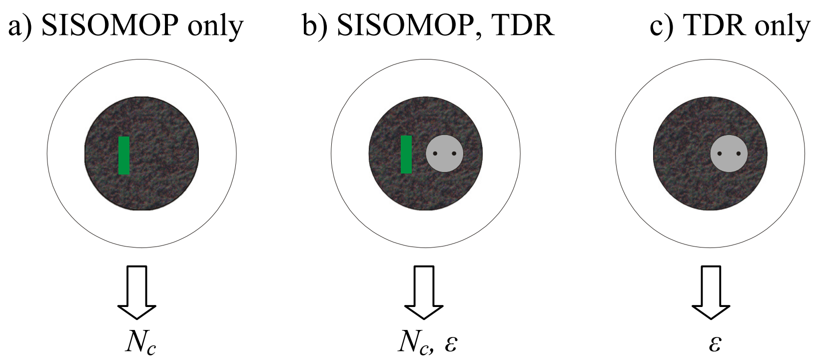


Fig. 6 Investigation of minimum distances between SISOMOP, TDR-rod-probe and soil-boundary

As a result of these preliminary investigations the optimal size of the soil sample has a diameter between 18 and 20 cm. The height of the sample depends on the length of the probes plus an additional overhead of 3 to 4 cm on the top and bottom layer.

The cylindrical-shaped soil sample is surrounded by a thin plastic meshwork to allow evaporation and prevent damaging. The whole sample is also placed on a grid so that free water can leak out of the soil.

## 3.2 Calibration

The electrical measurement devices described in the previous section lead to an indirect determination of the soil moisture content. These measurements require a calibration function between the electrical and the soil-physical parameters. To get permanent measurements of the gravimetric water content of the soil sample the total test equipment has been placed on an electronic weighing machine (Fig. 7). The volume of the soil sample can easily be calculated by measuring the soil-cylinder and probe dimensions. With this additional information the volumetric water content can also be calculated.

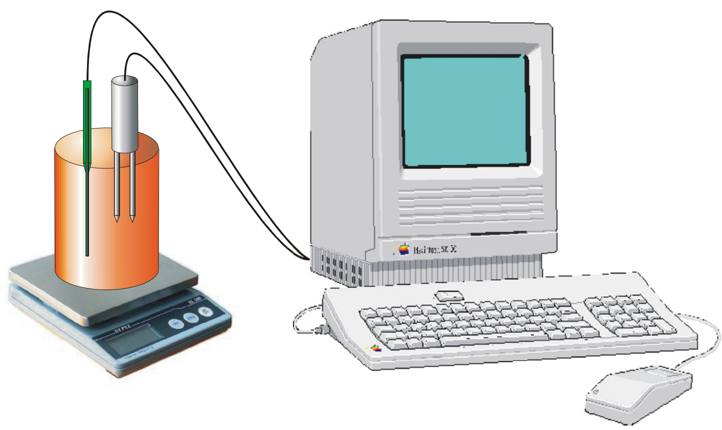

Fig. 7 Schematic view of the calibration-equipment using SISOMOP, TDR-rod-probe and an electronic weighing machine

To start one calibration experiment the soil is saturated between 70 and 80 % of its pore volume. Then the material is manually filled into a rigid pipe segment which is covered inside with a plastic meshwork. During the filling procedure the two moisture probes are inserted into the material. After the filling procedure the stabilising pipe segment is removed.

When the soil sample is placed on the weighing machine a computer collects $N_c(t)$ from the SISOMOP, dielectric permittivity $\varepsilon(t)$ from the TDR-probe and the gravimetric water content $\theta_g(t)$ from the electronic weighing machine.

One calibration experiment takes about one to three weeks to reach a steady state of dry material depending on the soil type (sandy soil dries out much faster than clayey material). To compare field taken moisture counts $N_c$ with its corresponding water content three different calibration experiments with silty soil were carried out (sample-1: silty material from Untergrombach, Germany, dry density $\rho$ = 1.3 g/cm$^3$, sample-2: silty material from Vicunia, Chile, $\rho$ = 1.6 g/cm$^3$, sample-3: same location than sample-2 but $\rho$ = 1.5 g/cm$^3$).

Fig. 8 shows the relation between the moisture count $N_c$ and the dielectric permittivity $\varepsilon$. As one can see the moisture count and the dielectric permittivity are correlated and do not depend on the material properties. Nevertheless future calibration experiments with sand or clay have to prove this assumption.

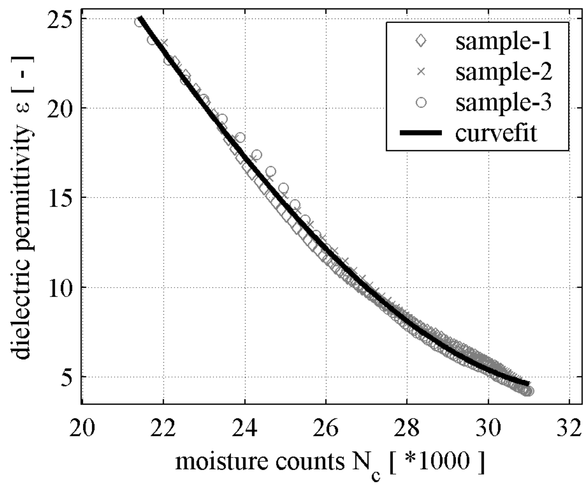


Fig. 8 Relation between SISOMOP moisture-counts and dielectric permittivity measured with TDR-rod-probes

The relation between the moisture count $N_c$ and the dielectric permittivity $\varepsilon$ can be described with a polynomial of third class to fit all three calibration data-sets.

$$\varepsilon = 5.15 \cdot 10^{-12} N_c^3 - 2.684 \cdot 10^{-7} N_c^2 + 1.208 \cdot 10^{-3} N_c + 71.66 \qquad (1)$$

When using known material dependent transformation functions between and $\varepsilon$ and $\theta_v$ the water content can easily been calculated. Using the standard transformation developed by Topp et al. [6] the relation between moisture count $N_c$ and water content $\theta_v$ becomes approximately linear (see Fig. 9).

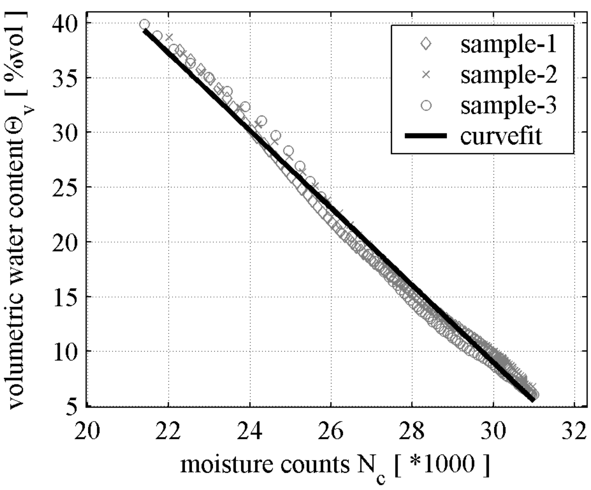


Fig. 9 Relation between SISOMOP moisture-counts and volumetric water content using $\varepsilon$-calibration from Fig. 4 and empirical $\varepsilon$-$\theta_v$-relation according to Topp et al.

This relation can be described by

$$\Theta_v = -3.531 \cdot 10^{-3} N_c + 114.9 \tag{2}$$

## 3.3 Experimental Results

The volumetric water content $\theta_v$ from (2) is determined by the dielectric permittivity ε of the soil using a standard transformation that has been developed empirically for many soil types. But this water content may vary from the soil-specific water content measured gravimetrically. Therefore the weight measurements were added to receive a better conversion from moisture count $N_c$ to actual water content.

Fig. 10 shows the relation between moisture counts and gravimetrically determined water content. One can see that different materials (sample-1 from Germany, sample-2 and 3 from Chile) may lead to different calibration functions. The wet materials (15 to 35 %vol) behave similar whereas the dry materials (4 to 15 %vol) lead to different moisture counts. There are no important variations between two different installations of the same material (sample-2: $\rho = 1.6$ g/cm$^3$, sample-3: $\rho = 1.5$ g/cm$^3$).

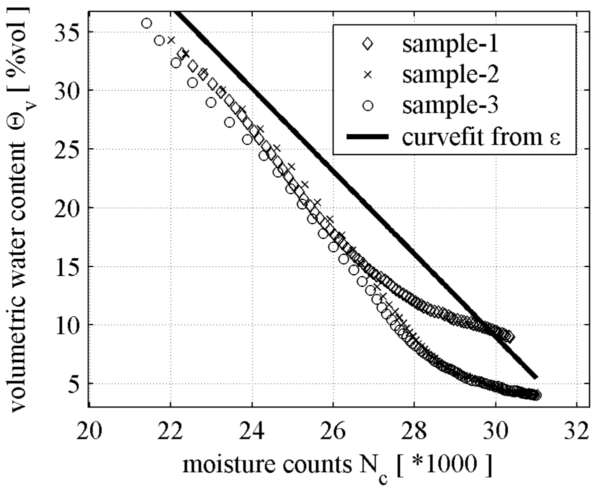


Fig. 10 Relation between SISOMOP moisture-counts and volumetric water content which was determined gravimetrically on a electrical weighing machine (the standard calibration function from Fig. 9 is also included to see the deviation between these two methods)

This calibration procedure leads to material-dependent calibration functions to describe the correlation between moisture counts $N_c$ and volumetric water content $\theta_v$. The Untergrombach-material (Germany) can be described with

$$\Theta_v^1 = 1.246 \cdot 10^{-11} N_c^3 - 7.144 \cdot 10^{-7} N_c^2 + 8.429 \cdot 10^{-3} N_c + 62.99 \tag{3}$$

and the Vicunia-material (Chile) with

$$\Theta_v^{2,3} = 1.369 \cdot 10^{-11} N_c^3 - 8.358 \cdot 10^{-7} N_c^2 + 1.166 \cdot 10^{-2} N_c + 37.52\,. \tag{4}$$

These calibration functions were successfully used in field experiments on the two test sites.

## 4 Conclusion

A simple soil moisture probe has been developed based on the ring oscillator principle. The transmission line in the feedback loop is etched on a printed circuit board which can be inserted in the material of interest. In combination with an onboard temperature sensor and a material specific calibration reliable long-term measurements of water content are achieved. Cost sensitive applications may profit from the simple and economical design.
To calibrate this new type of moisture sensor a combined electrical and gravimetrical calibration procedure has been tested. It leads to a material-independent relation between the dielectric permittivity and the counts from the moisture probe. This allows on site water content measurements without knowledge of the tested soil. To enhance the quality of the water content determination a soil-specific calibration is required. The presented calibration procedure leads to material-dependent calibration functions.

## References


1. Woodhead, I., 1992, Dielectric Constant Monitor, U.S. Pat. No. 5,148,125
2. Hocker, L.O., 2000, Sensing Water and Moisture Using a Delay Line, U.S. Pat. No. 6,060,889
3. Anderson, S.K., 2003, Absolute-Reading Soil Moisture and Conductivity Sensor, U.S. Pat. No. 6,657,443
4. DeHart, S.A., 2004, System and Method for Measuring Moisture Content in a Conductive Environment, U.S. Pat. No. 6,798,215
5. Maxim, 2002, DS18B20 programmable resolution 1-wire digital thermometer, data sheet, http://pdfserv.maxim-ic.com/en/ds/DS18B20.pdf
6. Topp, G.C., Davis, J.L., Annan, A.P., Electromagnetic determination of soil water content: measurement in coaxial transmission lines, Water Resources Research 16, 574-582, 1980.



Contact point: Dr.-Ing. Stefan Schlaeger, Forschergruppe Feuchtemesstechnik, Soil Moisture Group (SMG), University of Karlsruhe, Kaiserstr. 12, 76128 Karlsruhe; Germany. Phone: +49-721-608-4059; Fax: +49-721-608-4203; E-mail: info@stefan-schlaeger.de