On the Design and Construction of Dual-Probe Heat-Pulse Soil Moisture Sensor: Towards an Industrial Solution

Antonio Valente*, Arata Andrade Saraiva†, N. M. Fonseca Ferreira‡, and Salviano Soares§

*INESC TEC - INESC Technology and Science
and University of Trás-os-Montes and Alto Douro
Vila Real, Portugal
Email: avalente@utad.pt
ORCID: 0000-0002-5798-1298

†CEUMA
and State University of Piaui-Piripiri
and University of Trás-os-Montes and Alto Douro,
Vila Real, Portugal
Email: aratasaraiva@gmail.com
ORCID: 0000-0002-3960-697X

‡INESC TEC - INESC Technology and Science
and Institute of Engineering of Coimbra,
Polytechnic Institute of Coimbra,
Coimbra, Portugal
Email: nunomig@isec.pt
ORCID: 0000-0002-2204-6339

§IEETA - UA
and University of Trás-os-Montes and Alto Douro,
Vila Real, Portugal
Email: salblues@utad.pt
ORCID: 0000-0001-5862-5706

***Abstract*—There is a need for a multi-functional probe for small-scale measurements of different soil properties measured within identical soil volumes. Dual Probe Heat Pulse (DPHP) sensors are an economical solution for this since they measure simultaneously temperature, volumetric water content, and soil thermal properties: diffusivity and volumetric heat capacity. However, all DPHP sensors to date have very complex manufacturing processes. This paper aims to design and build a DPHP sensor based only on a Printed Circuit Board (PCB) board, which comprises the probes and all supporting electronics leading to a low cost and simple manufacturing process. The proposed system includes signal-processing circuits, a microcontroller, and communicates by a Serial Digital Interface at 1200 baud protocol (SDI-12). Probe spacing calibration results showed a reasonably good agreement between measured and fitted data. In conclusion, results also show that it is possible to build the multi-functional DPHP sensor in a low cost process, and this was the first time that a multi-functional probe was build using a Printed Circuit Board (PCB) as support.**

***Keywords*–soil moisture sensor; soil thermal properties; dual-probe; heat-pulse sensor; thermal conductivity; thermal sensors.**

I. INTRODUCTION

The heat pulse-based soil moisture sensors, of which stand out Dual Probe Heat Pulse (DPHP) sensors, are an economical solution for soil moisture measurements. Since Campbell [1], much research has been done and reported that the heat pulse technique is an economical technique to measure soil thermal properties and soil moisture content [1]–[19]. The DPHP-based sensor has two elements, the heat probe and the temperature sensor probe, separated by a short distance, r. A voltage pulse, with finite duration t_0, is applied to the heater element causing the heat to flow in all directions around the heater element. Heat 'traverses' the surrounding soil and the temperature rise will be measured by a sensor on the temperature probe. However, in almost all developed sensors [1]–[14], the heating probe is composed of a needle where a conductive wire (with a high resistivity, suitable for producing resistances for heating) is inserted inside. The probe with the temperature sensor is elaborated in the same way, by inserting the temperature sensor (thermocouple or thermistor) inside a needle. Both needles are then filled with an epoxy glue of high thermal conductivity and low electrical conductivity. Therefore, the use of this process is laborious and difficult, if not impossible, for industrialization. Other authors have attempted, without known success, to develop soil moisture sensors based on the heat pulse without the use of needles. In this group, there are the works of [15]–[17], [19] who developed microelectronics to try to improve the manufacturing process and in other works a button-shaped sensor was developed [14], [18]. Most of the work done with DPHP sensors uses data-loggers to acquire data from temperature probe, to control heat pulse duration and to perform calculations. A recent work [12] overcomes this problem but still uses needle type probes. In this paper, we resolve these shortcomings. In particular, we make the following contributions:

- Place all the electronics near the probes (heating and temperature probes). This contribution (Section III), although already achieved by [12], uses only a temperature probe, making the construction of the sensor simpler at the expense of measuring the flow of water in the soil.
- We present a new form of sensor construction which uses the PCB, also used for the rest of electronics, as a support for the temperature and heating probes (Section III). This is a great achievement as it will enable the industrial production of the sensor at a reduced cost.
- All calculations of the model used (Section II) are performed inside of the on-board microcontroller. The results of the calibration using agar (Section IV) showed good results of the model used.

The rest of this paper is organized as follows. Section II describes the models implemented for the calculation of the soil thermal properties and volumetric water content. Section III details all the fabrication process of the DPHP sensor, calibration method of the distance between heater and temperature sensor, and SDI-12 communication commands implemented. Section IV addresses the sensor calibration results and shows sensor prototypes. The acknowledgement and conclusions close the article.

II. THEORY

There are some models to describe the operation of sensors based on the DPHP method. The simpler model, described by Campbell [1], considers that the heat source is an infinite line and the heat pulse is released instantaneously. The other models [2] increase the constraints of the model of Campbell, considering that the heat pulse is finite, that the source line is finite and, finally, that it is not a source line, but a cylinder. Of these models the most common is the model which considers the finite heat pulse generated by an infinite source line [2]. In the present work, this will be the adopted model due to its precision and relative ease implementation in a microcontroller-based system. The solution for conducting radial heat from a short-duration, t_0 , heat pulse away from an infinite source line, for $t > t_0$ is

$$\Delta T(r,T) = \frac{q'}{4\pi\kappa\rho c}\left[\mathrm{E_i}\left(\frac{-r^2}{4\kappa(t-t_0)}\right) - \mathrm{E_i}\left(\frac{-r^2}{4\kappa t}\right)\right] \quad (1)$$

where, ΔT is change in temperature ($^\circ C$), r is radial distance from the line source (m), t is time (s), q' is the energy input per unit length of heater per unit time ($\mathrm{W\,m^{-1}}$), ρc is the volumetric heat capacity ($\mathrm{J\,m^{-3}\,^\circ C^{-1}}$), κ is the thermal diffusivity ($\mathrm{m^2\,s^{-1}}$) of the medium surrounding the heater, and $-\mathrm{Ei}(-x)$ is the exponential integral [20]. The thermal diffusivity (κ) and volumetric heat capacity (ρc) can be determined from heat-pulse measurements using the single-point method [3], or a nonlinear curve fitting where (1) is fitted to measured $\Delta T(r,t)$ data [5]. It was showed that, accuracy in ρc will be limited by the accuracy of r, and accuracy in κ will be limited by the accuracy of both r and time of maximum temperature change, t_M [3]. The single-point method makes use of the fact that the temperature response at some distance r from the heater displays a maximum, so that we can take the derivative of (1) with respect to time, set the result equal to zero, and obtain the time, t_M, to the maximum temperature change (ΔT_M). This yields an expression for estimating κ where

$$\kappa = \frac{r^2}{4}\left[\frac{\frac{1}{(t_\mathrm{M}-t_0)} - \frac{1}{t_\mathrm{M}}}{\ln\left(\frac{t_\mathrm{M}}{t_\mathrm{M}-t_0}\right)}\right] \quad (2)$$

which is a function of r, t_M and t_0. Rearrangement of (1) yields an expression for estimating ρc, for $t > t_0$,

$$\rho c = \frac{q'}{4\pi\kappa\Delta T_\mathrm{M}}\left[\mathrm{E_i}\left(\frac{-r^2}{4\kappa(t-t_0)}\right) - \mathrm{E_i}\left(\frac{-r^2}{4\kappa t}\right)\right] \quad (3)$$

where κ is obtained from (2). To minimize errors, the single-point method requires an accurate measurement of r and times t_M and t_0. For ρc estimation, in addition to κ from (2) and r, are needed accurate measurements of q' and ΔT_M. Volumetric heat capacity ρc of soil can be determined as the sum of the heat capacities of the individual constituents and considering that the air is ignored and solids defined to include the mineral and organic matter fractions then soil water content θ_v can be defined as a function of volumetric heat capacity [21],

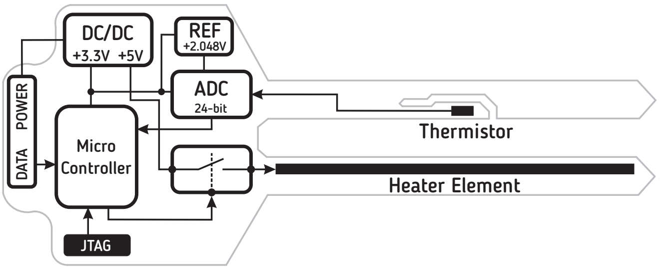

Figure 1. Sensor overview

$$\theta_\mathrm{v} = \frac{\rho c - \rho_\mathrm{b} c_\mathrm{s}}{(\rho c)_\mathrm{w}} \quad (4)$$

where ρ is density, c specific heat, θ_v volumetric water content, and the subscripts b, s and w indicates bulk, average properties of the solids (minerals+organic matter), and water, respectively. Since $(\rho c)_\mathrm{w}$ is known, measurements of ρc obtained with the sensor can be used together with estimates (or preferably measurements) of soil bulk density (ρ_b) and specific heat (ρ_s) to obtain θ_v.

III. MATERIALS AND METHODS

The developed sensor is a complete solution and this approach, together with the non-use of needles for the heating and temperature probes, is new. Next, all details of the sensor construction, as well as its firmware, the communication protocol and as referred to in the previous section the knowledge of the true value of r (r_eff) through calibration in agar, will be explained in detail.

A. Sensor System Description

In Figure1 is depicted the electronic layout of the sensor system, the core unit is on-board 16 bit microcontroller (PIC24F32KA301) with very low power consumption, 12-channel 12 bit Analog-to-Digital Converter (ADC), serial communications modules (UART - Universal Asynchronous Receiver-Transmitter, SPI - Serial Peripheral Interface, and $\mathrm{I^2C}$ - Inter-Integrated Circuit), and hardware Real-Time Clock (RTC) Calendar with alarms. The temperature sensor probe consists of a $10\,\mathrm{k\Omega}$ (NCP15XH103F03RC) thermistor, a precision ($0.1\,\%$) voltage reference of $2.048\,\mathrm{V}$ (LM4128) and a 24 bit ADC (MCP3421). The heating probe consists of a series of 15 resistors of $1\,\Omega$, controlled by an electronic switch composed of transistors. The system power is from the SDI-12 power ($6\,\mathrm{V}$ to $12\,\mathrm{V}$) that feeds a dual DC regulator: $2\,\mathrm{V}$ to $5\,\mathrm{V}$ for powering the heat pulse (LM1117), and $3.3\,\mathrm{V}$ for the rest of the system (MIC5219).

The microcontroller controls the heat pulse through the transistors switch to enable/disable the power to the heater. To determine accurately the value of q' (heat input per unit

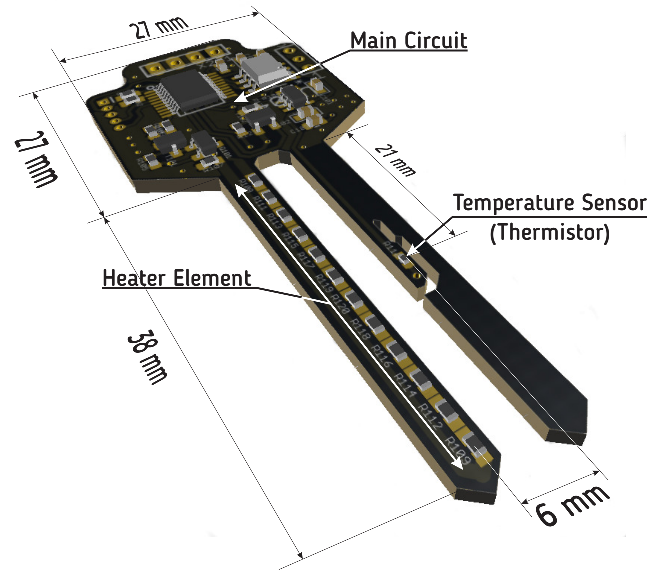

Figure 2. Sensor 3D view.

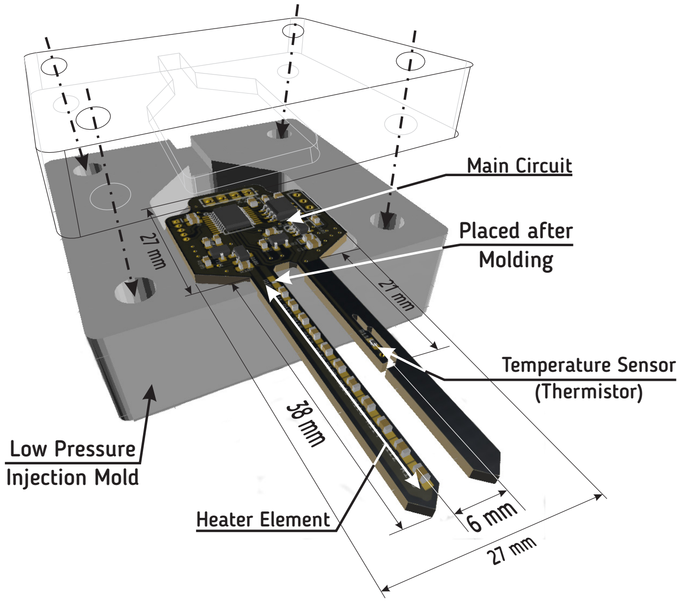

Figure 3. 3D view of the construction details.

length per unit time), average current through the heater was determined by sampling the voltage across a $0.18\,\Omega$ resistor ($1\,\%$) in series with the heater $15\,\Omega$ resistor ($15 \times 1\,\Omega$), and the voltage across resistance series of the heater and current measure resistor. The value q' is determined by

$$q' = V_{\text{heater}} \times I_{\text{heater}} \times \frac{1}{l_{\text{heater}}} \qquad (5)$$

where V_{heater} is the measured voltage across the heater, I_{heater} is the current through the heater given by $I_{\text{heater}} = V_{\text{R}=0.18}/0.18\,\Omega$ ($V_{\text{R}=0.18}$ is the measured voltage across the $0.18\,\Omega$ resistor), and l_{heater} is the length of the heater ($0.0353\,\text{m}$). All voltages measured for q' calculations, are performed by microcontroller internal ADC ($12\,\text{bit}$). Temperature from the temperature probe was measured by sampling the voltage drop across the thermistor in series with a $10\,\text{k}\Omega$ ($0.1\,\%$) resistor. This was done on the $24\,\text{bit}$ ADC to ensure sufficient sampling accuracy for determining temperature.

B. Sensor Construction

The prototype of the developed sensor, as shown in Figure 2, is based on the printed circuit board (PCB) as substrate. In the PCB are welded all the components necessary for the operation of the sensor. The design of the PCB was made in the form of a fork with two 'rods' that form the heating probe and the temperature probe. The thermistor in the temperature probe is placed in a thermally insulated tab. The distance between these two elements were designed to be $6 \times 10^{-3}\,\text{m}$. However, this distance has to be calibrated because as previously described an error in this parameter contributed significantly to the error in the determination of κ and ρc [4].

The process of mounting the sensor is as follows:

- Manufacture of PCB board;
- Assembly of all electric components, except for the first resistance of the heating element due to the mold;
- Sealing, using a mold as depicted on Figure 2, with thermoplastic molding resin to achieve high quality sealing and protection of components of the main circuit. Overtec 820 15 Hotmelt Glue Gun, from Techsil Limited, UK, was used with the respective polyamide resin OverTec 5 FR;
- Missing resistor placement;
- Placement of an epoxy adhesive in the heating element (in all resistors forming it) and in the thermistor.

As can be seen from the description of the process used for the elaboration of the prototype, it can be turned into an industrial process.

C. Firmware

The developed firmware, after all the initialization, enters into sleep mode waiting for a SDI-12 command. After a `aM!` command the firmware will perform a complete measurement as presented on Figure III-C.

The presented values for the heater voltage ($5\,\text{V}$), the heating duration ($8\,\text{s}$) and the time allowed for the next measurement are the defaults. These values can be change as described next.

D. Digital Communications

The sensor uses SDI-12 protocol for digital communication of sensor data and change sensor parameters. SDI-12 is a standard to interface battery powered data recorders with micro-processor based sensors designed for environmental data acquisition. All SDI-12 communications are transmitted using American Standard Code for Information Interchange (ASCII) at 1200 baud with 7 data bits and an even parity bit. The standard also specifies a communications protocol that allows sensors to remain in a low-power sleep state until awoken by a serial break signal sent by the master. The first character of each command is a unique sensor address, `a`, that specifies with which sensor the recorder wants to communicate. Table I lists

```
repeat    ▷ Read soil temperature before applying heat
    $StartTemperature \leftarrow temperature$
until $time < 12\,\mathrm{s}$
HeatPulse ON ($5\,\mathrm{V}$)
repeat    ▷ Read heat power
    $HeatVoltage \leftarrow voltage$
    $HeatCurrent \leftarrow current$
until $time < 8\,\mathrm{s}$
HeatPulse OFF
Calculate $q'$ using (5)
repeat    ▷ Read Temperature Increase
          ▷ (3 samples/second)
    $\Delta T \leftarrow temperature - StartTemperature$
    DetectMaxTemperature ($\Delta T_\mathrm{M}$, $t_\mathrm{M}$)
until $time < 120\,\mathrm{s}$
Calculate $\kappa$ using (2)
Calculate $\rho c$ using (3)
Calculate $\theta_\mathrm{v}$ using (4)
Enter SLEEP mode ($760\,\mathrm{s}$)
```

Figure 4. Firmware algorithm

all the commands that the sensor will respond to. In addition to the standard commands it was necessary to implement a set of extended commands (with an `X` after the address) in order to configure the sensor and obtain individual readings of some parameters. These extended commands uses letter `G` after the `X` to get extra data from the sensor (heater voltage, heating power, heater current, spacing between heater and temperature sensor, maximum temperature rise, time of the maximum temperature rise, soil bulk density, and individual sensor parameters readings: soil volumetric water content, soil thermal diffusivity, and volumetric heat capacity), and a letter `S` to set new values for heater applied voltage and heat duration, to new spacing value, and to set new bulk density. Access to metadata is also available as presented in version 1.4 of the SDI-12 specification [22]. For calibration and whenever necessary, the raw values ($16\,\mathrm{bit}$ unsigned floating point format) of the temperature curve can be requested using the High Volume Binary Command (`aHB!`).

E. Probe Distance Calibration

The measurement of κ and ρc are highly sensitive to effective separation distances, r, between the heater element on heater probe and the thermistor on temperature sensor probe [4]. Thus, calibration of this distance was crucial for accurate measurements. The calibration was performed by inserting the sensor in a gel that was made from a $4 \times 10^{-3}\,\mathrm{kg\,L^{-1}}$ agar solution, Figure 5. The agar has equal thermal properties as water, yet does not create heat convection as would occur by heating liquid water [1].

The measured temperature response in agar solution was used to calibrate the sensor separation distance for each thermistor by fitting the measured temperature change to (1) using known values of volumetric heat capacity ($4174\,\mathrm{kJ\,m^{-3}\,K}$) and thermal diffusivity ($1.436 \times 10^{7}\,\mathrm{m^2\,s^{-1}}$) of water.

IV. RESULTS AND DISCUSSION

Since this work is only about a description of the design and the construction of the sensor, only the results about the sensor assembly and the calibration of the distance between the probes will be discussed.

A. Assembled Sensor

Figure 6 shows the assembled sensor without the thermoplastic molding resin and the final version of the sensor. The sensor is small in size, compact, robust and easy to use. The final product is comparable to commercial versions of other soil moisture sensors using other measuring methods, such as the EC-5, 5TE and 5TM probes from Decagon Devices Inc., USA.

This type of sensor (DPHP sensor) compares with capacitive type of sensor in terms of accuracy ($\pm 3\,\%$ [23]), and is very different from very low-cost resistive sensor. Resistive sensors give only qualitative estimation of the moisture content [23].

B. Probe Distance Calibration

The probe distance calibration was determined by obtaining five sensor readings in agar solution with an interval of $1\,\mathrm{h}$ between readings and with heating power of $q' = 51.65\,\mathrm{W\,m^{-1}}$. Figure 7 presents the measured temperature response as a function of measurement time of one of these readings. The measured temperature data was fitted using the nonlinear least-squares Marquardt-Levenberg algorithm. There is a good agreement between measured and fitted data. The fitted values of effective separation distance, r_eff, for all 5 readings are presented in Table II. The average value of r_eff is $5.534 \times 10^{-3}\,\mathrm{m}$. The differences between the designed PCB layout value ($6 \times 10^{-3}\,\mathrm{m}$) and effective distances are likely caused by unprecise placement of the components (heater

Figure 5. Probe distance calibration in agar solution

TABLE I. SDI-12 SENSOR COMMANDS

Command	*Description*	*Command*	*Description*
?!	Return address of the sensor	aI!	Return sensor identification
aAb!	Change actual address to new 'b' address	aXGQ!	Return heating power, q', value
aM!	Start all measurements	aXGV!	Return heater applied voltage
aM1!	Start soil temperature measurement	aXSVn.n!	Assign heater voltage (from 2.0 to 5.0 V)
aD0!	Read measurements data	aXGT!	Return maximum temperature rise, ΔT_{M}
aHB!	Raw data of temperature curve	aXGH!	Return heat duration, t_0
aXGP1!	Return soil volumetric water content, θ_{v}	aXGI!	Return heater current
aXGP2!	Return soil thermal diffusivity, κ	aXGR!	Return spacing, r, value
aXGP3!	Return soil volumetric heat capacity ρc	aXSRn.nnn!	Assign new spacing value (from 5.500 to 6.500 mm)
aXGB!	Return soil bulk density, ρ_{b}	aXSHnn!	Change heat duration (from 6 to 30 s)
aXSBm.nn!	Set soil bulk density (from 0.90 to 2.00 $10^3\,\mathrm{kg\,m^{-3}}$)		

and/or thermistor) because they are hand welded. In an industrial process this error could be minimized and lead to two kinds of sensors: agar calibrated and uncalibrated lowering the costs.

It can also be observed in the Figure 7 that, compared to other works [3], [9], [24], just to mention a few, that uses datalogger for reading and control of the DPHP sensor, this prototype presents a better resolution ($18\,\mathrm{bit}$ against $13\,\mathrm{bit}$ of must dataloggers) and a better sampling rate (1 sample/s against 3 samples/s). This will give a better precision on calculating ΔT_{M} and t_{M}. We can also observe a good signal to noise ratio ($\Delta T_{\mathrm{M}} = 0.3728\,°\mathrm{C}$ for a value of $100\,\%$ of θ_{v}, agar $\Rightarrow$ water) even for a lower heat power ($51.65\,\mathrm{W\,m^{-1}}$ against $60\,\mathrm{W\,m^{-1}}$ - minimum found in literature [3]). This low power (could be less and adjusted depending on θ_{v} values - lower values less power) is very important in order to use the sensor in wireless systems (Internet of Things - IoT).

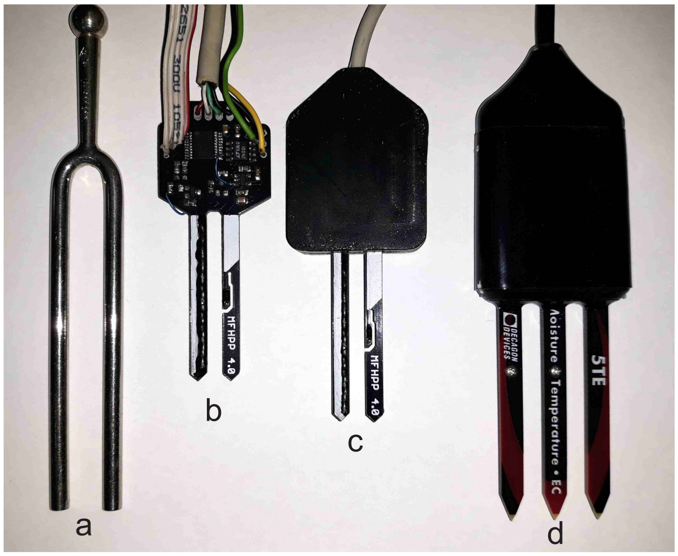

Figure 6. Developed prototypes of the DPHP sensor. a) Diapason; b) Prototype for debug without protective resin; c) Final prototype with protective resin; d) Decagon 5TE.

TABLE II. CALIBRATION OF THE EFFECTIVE SPACING, r_{eff}

Sensor Readings	$r(\mathrm{m})$	$r_{\mathrm{eff}}(\mathrm{m})$
#1	0.006	0.005566
#2		0.005522
#3		0.005521
#4		0.005512
#5		0.005551
Average		**0.005534**

V. CONCLUSION AND FUTURE WORK

This paper presents a novel design and an industrial process to build a DPHP sensor based on PCB board as substrate. The process is based on four steps and a calibration process in agar. Results also show that it is possible to build the multi-functional DPHP sensor in a low cost industrial process (PCB and assembly). This was the first time that a soil moisture sensor, based on heat-pulse method, was build using a PCB as support. Further work must be done to find out the sensor accuracy, test sensor readings variations with soil type, and perform in-field and long-term stability tests.

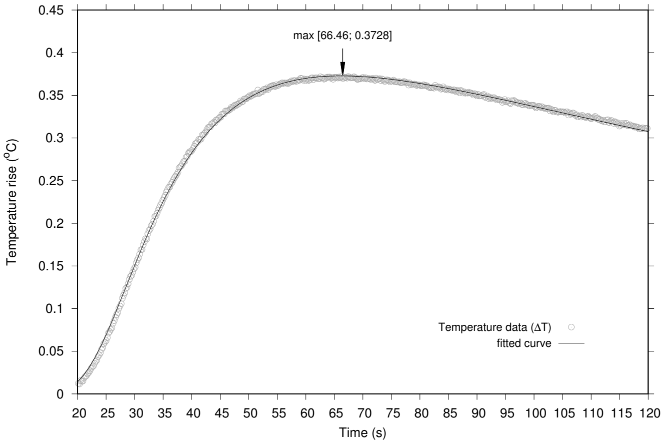

Figure 7. Measured temperature rise after the heat pulse in agar solution compared to the analytic modeled data (solid line).

In addition, as the sensor has a PCB as substrate, pads can be placed to measure soil moisture using the capacitive method and to measure soil Electrical Conductivity (EC).

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