DEVELOPMENT OF AN OPEN HARDWARE PORTABLE DUAL-PROBE HEAT-PULSE SENSOR FOR MEASURING SOIL THERMAL PROPERTIES AND WATER CONTENT

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KEY POINTS

- *The Dual-Probe Heat-Pulse sensor allows to measure water content and thermal properties of a small control volume of soil*
- *A portable sensor was developed based on open hardware / open software Arduino© architecture*
- *Result show that the sensor has the same accuracy as the traditional time-domain reflectometer for water content assessment*

1 INTRODUCTION

Soil thermal properties are of great interest in many scientific and engineering applications concerning coupled heat and water transport across the vadose zone (*Ravazzani et al.*, 2011; *Ravazzani et al.*, 2015), estimate of soil surface water content from thermal inertia distributions retrieved from remotely sensed images (*Minacapilli et al.*, 2012), and, more generally, in agronomy and soil science.

In recent years considerable effort has gone into developing techniques to determine soil thermal properties. One technique that has received attention employs heat-pulse technology (*Campbell et al.*, 1991). Several authors proposed construction schemes for Dual-Probe Heat-Pulse (DPHP) sensors (*Ham & Benson*, 2004). Recent advances show an increase in the use of “open hardware” platforms for scientific instrumentation and research. “Open hardware” philosophy aims at providing free and transparent access to hardware design and code in analogy with the concept of “open source software” (*Bitella et al.*, 2014). Indeed, open hardware is the logical evolution of the open source software applied to physical stuff, where both code and design blueprints co-exist.

The objective of this work is testing a portable low cost - open hardware portable device based on Arduino© technology, for the measurement of soil thermal properties and water content.

2 MATERIALS AND METHODS

2.1 The dual-probe heat-pulse method

The temperature rise, ΔT (K), at a distance *r* (m) from the heater needle of the heat-pulse probe, after application of heat impulse during t_0 (s) can be expressed as (*Kluitenberg et al.*, 1993):

$$\Delta T(r,t) = \begin{cases} -\dfrac{Q'}{4\pi\kappa} Ei\left(\dfrac{-r^2}{4\kappa t}\right) & 0 < t \le t_0 \\ \dfrac{Q'}{4\pi\kappa}\left\{ Ei\left[\dfrac{-r^2}{4\kappa(t-t_0)}\right] - Ei\left(\dfrac{-r^2}{4\kappa t}\right)\right\} & t > t_0 \end{cases} \quad (1)$$

where *t* is time from beginning of heating, Q' is the source strength per unit time (m^2 K s^{-1}), κ is the thermal diffusivity (m^2 s^{-1}) of the medium surrounding the heater, and -*Ei*(-*x*) is the exponential integral function with argument *x*. Q' is defined as $Q' = q'/\rho c$, where q' is the energy input per unit length of heater per unit time (W m^{-1}) and ρc is the volumetric heat capacity (J m^{-3} K^{-1}). The thermal diffusivity, κ, and volumetric heat capacity, ρc, can be determined using the single-point method (*Bristow et al.*, 1994). Soil thermal properties can be expressed as:

$$\kappa = \frac{r_n^2}{4}\left\{\frac{1/(t_m - t_0) - 1/t_m}{\ln[t_m/(t_m - t_0)]}\right\} \tag{2}$$

and

$$\rho c = \frac{q'}{4\pi\kappa\Delta T_m}\left\{Ei\left[\frac{-r_n^2}{4\kappa(t_m - t_0)}\right] - Ei\left(\frac{-r_n^2}{4\kappa t_m}\right)\right\} \tag{3}$$

where r_n is the needle spacing of the DPHP (m), t_m is the time of the maximum temperature change (s), and ΔT_m is the maximum temperature increase (K) as recorded from the DPHP thermistor. After κ and ρc have been determined, thermal conductivity, λ (W m^{-1} K^{-1}), can be obtained by definition as:

$$\lambda = \kappa \cdot \rho c \tag{4}$$

Volumetric heat capacity of soil can be determined as the sum of the heat capacity of water and solid, ignoring contribution given by air and defining solid to include the mineral and organic matter fractions:

$$\rho c = (\rho c)_s \phi_s + (\rho c)_w \vartheta_v \tag{5}$$

where ϕ_s is the volume fraction of soil (= (1-P) with soil porosity), $(\rho c)_s$ is the volumetric heat of soil solid, $(\rho c)_w$ is the volumetric heat of water, and ϑ_v is the volumetric water content. Because $(\rho c)_w$ is known, measurement of ρc obtained with the multi-needle probe can be used together with estimates or measurements of volumetric heat of soil to obtain ϑ_v .

2.2 Experimental setup

One experiment was conducted at the Fantoli Laboratory in the Politecnico di Milano to test the thermal properties and moisture determined by the DPHP probe on four soils of various.

Soil ID	Description	Origin	D_{50} (mm)	CU	Porosity (m^3/m^3)	Bulk density (Mg m^{-3})
1	Medium sand	River Toce, Vogogna-Prata	0.30	3.25	0.434	1380
2	Coarse sand	River Toce, Masone	0.45	4.83	0.390	1460
3	Sandy loam	Cultivated field, Bibione	0.20	5.00	0.344	1464
4	Fine sand	Beach, Bibione	0.22	3.79	0.376	1606

Tabel 1. Description, origin, median grain size, D_{50} (mm), coefficient of uniformity, CU, computed as the ratio between the grain diameter at 60% passing, and the grain diameter at 10% passing, porosity (m^3/m^3), and bulk density (Mg m^{-3})

The DPHP probe was calibrated in agar-stabilized water (5 g L^{-1}) to calculate the apparent spacing between the sensor probe and the heater probe (*Campbell et al.*, 1991). The DPHP probe was then used to assess thermal properties and water content of the different soil samples. In parallel to the measurements carried out with the DPHP, a portable device that measures soil moisture using Time Domain Reflectometer technique (TDR) was used for comparison. The TDR probe is constituted by four rods 60 mm long and 30 mm spaced.

Soil samples were oven dried at 105 °C and packed into two sets of containers. One set was dedicated to DPHP measurements and the other to TDR measurements. Volume and dimensions of the two types of containers were chosen in such a way that they are compatible to probe size and that measurements are representative of the entire soil sample.

The first set of measurements was acquired on dry soil samples for the assessment of solid sol thermal properties. After that, soil samples were saturated and measurements were repeated during time to let water content changing by evaporation. For each sample and for each water content, measurements were repeated three times. Each sample was weighed before and after each set of measurements in order to assess soil water content by gravimetric approach and to check that soil water change was not significant during the time required by measures.

Soil moisture estimates obtained from the DPHP and TDR probes and were compared against measurements from gravimetric method. The mean percentage error, *MPE*, mean absolute percentage error, *MAPE*, and normalized mean square error, *NMSE*, were calculated to evaluate the performance of DPHP and TDR methods

3 RESULTS AND DISCUSSION

The DPHP probe was used for assessing volumetric heat capacity of soil solid. Measures were repeated three times for each oven dried soil samples. From equation 5, as for dry soil contribution of water is not present, volumetric heat capacity of soil fraction, $(\rho c)_s$, can be computed as:

$$(\rho c)_s = \frac{\rho c}{1-P} \tag{6}$$

In Table 2, mean, standard deviation, and coefficient of variation of volumetric heat capacity of soil solid are presented. Obtained results, both in terms of mean value and standard deviation, are in agreement with values presented in literature (*Ren et al.*, 2003). Soil water content estimated with DPHP and TDR probes are reported in Figure 3 against gravimetric measurements. Performance indexes are shown in Table 3. Overall accuracy of DPHP and TDR water content estimates is good and comparable one each other. By analysing NMSE index, DPHP is more accurate than TDR in soil 1, 2, and 4, while TDR is more accurate in soil 3. Both DPHP and TDR present, on average, an underestimation in soil 1, 2 and 4 and overestimation in soil 3. TDR estimates show a significant overestimation under saturated condition, with values that even exceed soil porosity. Infact, while DPHP method uses physical properties of soil such as porosity and thermal properties for water content estimation, TDR method is based on an empirical relationship between soil dielectric constant and water content, thus no any physical constraint is considered unless soil specific calibration is undertaken.

Soil ID	Heat capacity (MJ m^{-3} K^{-1})	CV
1	2.392 ± 0.093	3.9
2	2.459 ± 0.085	3.5
3	2.494 ± 0.065	2.6
4	2.723 ± 0.044	1.6

Tabel 2. Mean, standard deviation, and coefficient of variation of volumetric heat capacity of soil fraction, based on three measurement replicates.

Soil ID	DPHP			TDR		
	MPE	MAPE	NMSE	MPE	MAPE	NMSE
1	-0.0953	0.1141	0.014	-0.0267	0.0984	0.027
2	-0.1134	0.1134	0.019	-0.0286	0.1008	0.027
3	0.2212	0.2536	0.045	0.1543	0.1543	0.040
4	-0.0849	0.1056	0.026	-0.0113	0.1469	0.054

Tabel 3. The mean percentage error, MPE, mean absolute percentage error, MAPE, and normalized mean square error, NMSE, computed on soil moisture measurements taken with DPHP and TDR.

4 CONCLUSIONS

In this paper, a portable probe for the assessment of soil thermal properties and water content using the DPHP method is presented. The DPHP probe is based on open hardware architecture that ensures a cost effective realization of the probe based on free sharing design. The DPHP probe has been tested for soil thermal properties assessment and compared to TDR probe for the water content estimation in four different soils. The DPHP probe showed an accuracy comparable to TDR in estimating water content, but the DPHP can be used to investigate smaller volume of soil. The counterpart is that TDR is much faster than DPHP in measure acquisition. TDR applied without a soil specific calibration overestimated water content under saturated condition.

Software is available at http://www.ravazzani.it/wp-content/uploads/2016/03/software_dphp.zip.

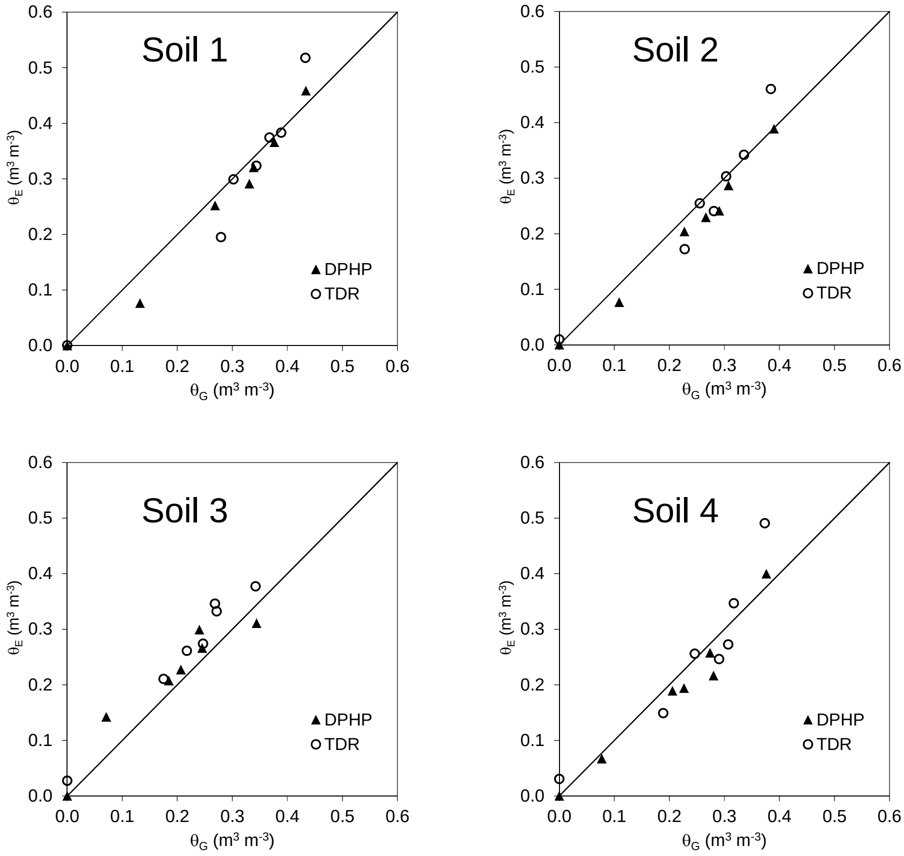

Figure 1. Comparison between soil moisture measured by gravimetric method, θ_G, and soil moisture estimated with DPHP and TDR probes for the four different soils. For each moisture level and soil samples, measurements were repeated three times.

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