→ MEASUREMENTS AND OBSERVATIONS IN THE 21st CENTURY CONFERENCE

Open hardware portable dual-probe heat-pulse sensor for measuring soil thermal properties and water content

Giovanni Ravazzani

POLITECNICO MILANO 1863

DIPARTIMENTO DI INGEGNERIA CIVILE E AMBIENTALE

21 November 2016 | ESA–ESRIN | Frascati (Rome) Italy

MOTIVATION

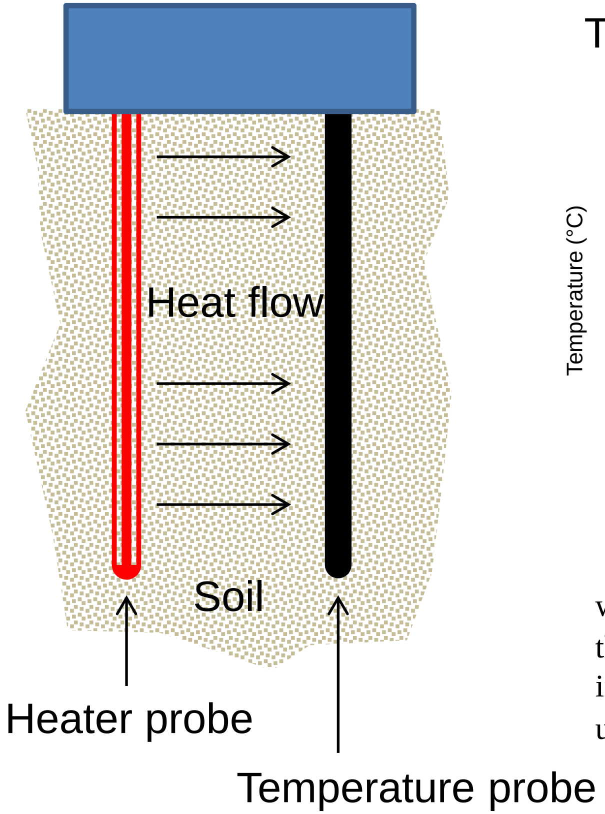
- Assessment of thermal soil properties, useful in many hydrological fields such as estimate of river-groundwater interaction or soil mositure estimation from satellite images using the thermal inertia method.

- Available portable equipments are very expensive, despite the basic methods to measure thermal properties are easy to implement. Measuring technique requires lots of energy, so batteries are short-lasting

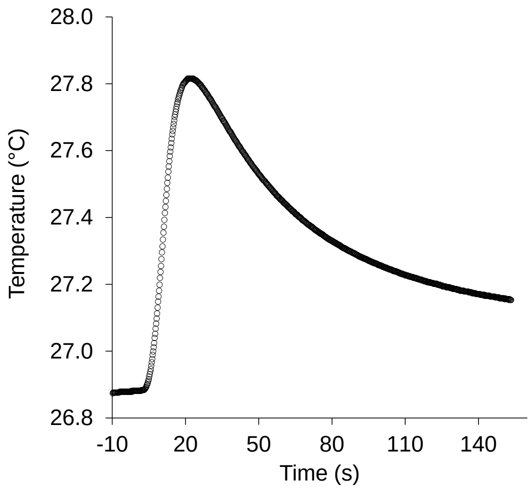
OBJECTIVE

- To build a low cost, portable, long-lasting device based on open-hardware technologies, for measuring soil thermal properties.

Theoretical background



Heat pulse of finite duration, emitted from a heat source.
Temperature rise recorded at a known distance from the emitter.



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

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 single point method

Volumetric heat capacity (J m^{-3} K^{-1})

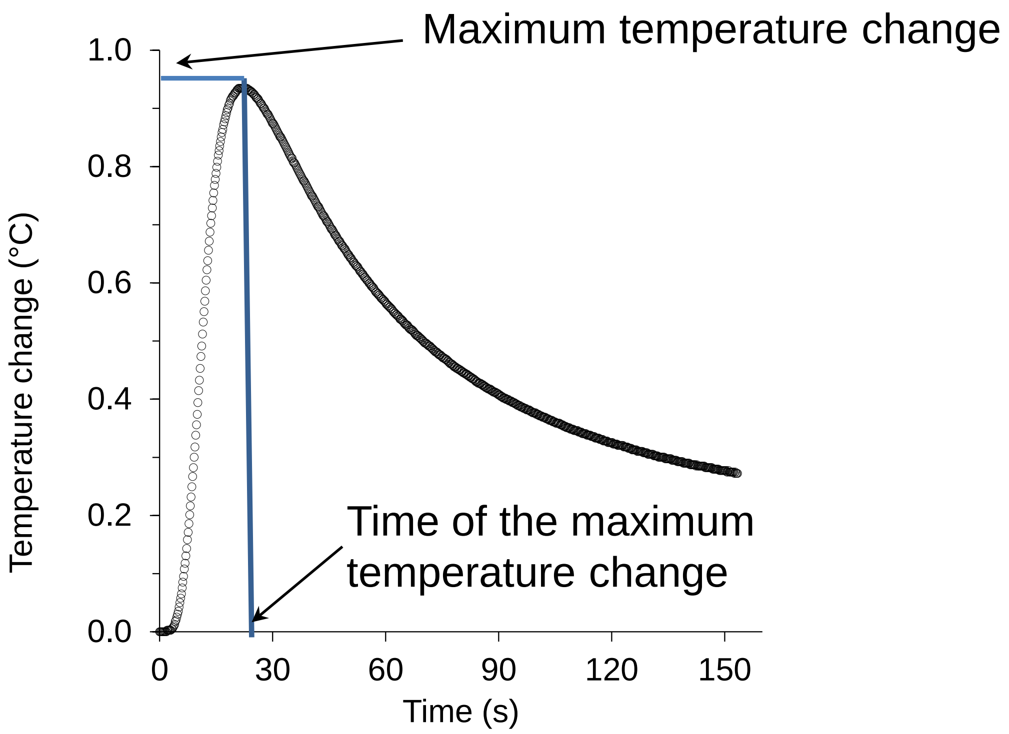
$$\rho c = \frac{q'}{4\pi\kappa\Delta T_m}\left\{Ei\left[\frac{-r_n^2}{4\kappa(t_m - t_0)}\right] - Ei\left(\frac{-r_n^2}{4\kappa t_m}\right)\right\}$$

Thermal diffusivity (m^2 s^{-1})

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

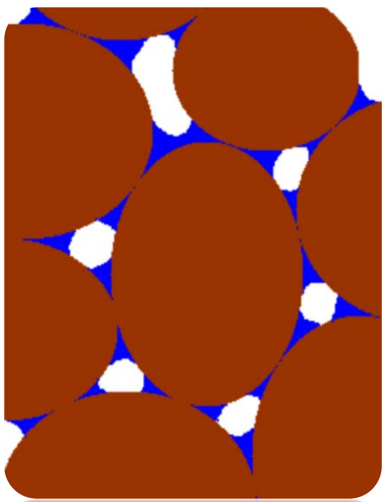
Thermal conductivity (W m^{-1} K^{-1})

$$\lambda = \kappa \cdot \rho c$$



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.

Soil moisture



Source: Canot É, et al. ASME. J. Heat Transfer. 2016

Fraction of soil solid

Heat capacity of water

$$\rho c = (\rho c)_s \phi_s + (\rho c)_w \vartheta_v$$

Heat capacity of soil solid

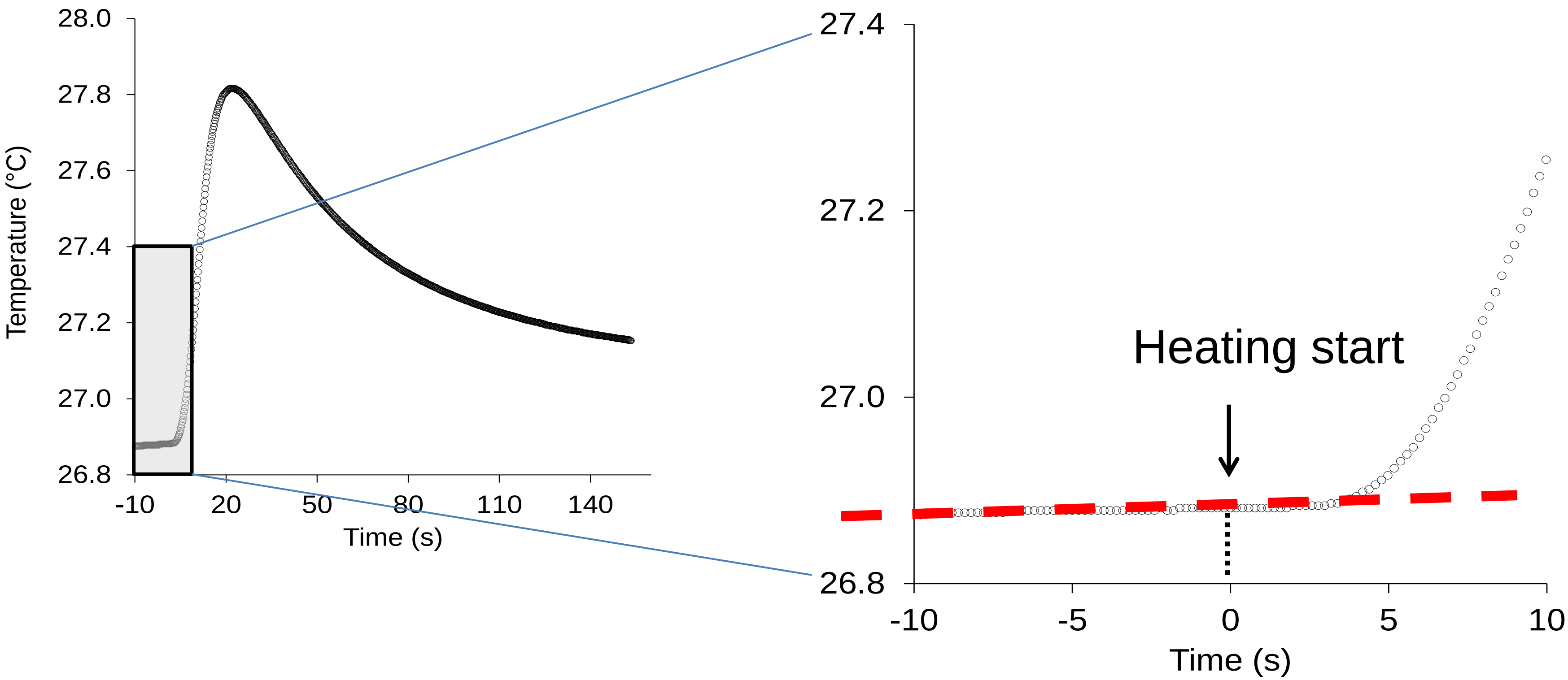
Unknown: water content

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, 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.

The developed equipment

ARDUINO

Correction for transient ambient temperature



Sensor spacing calibration

agar-stabilized water (5 g L^{-1}) (21° C)

$\lambda = 0.60106\ Wm^{-1}K^{-1}$

$\rho c = 4174000\ Jm^{-3}s^{-1}$

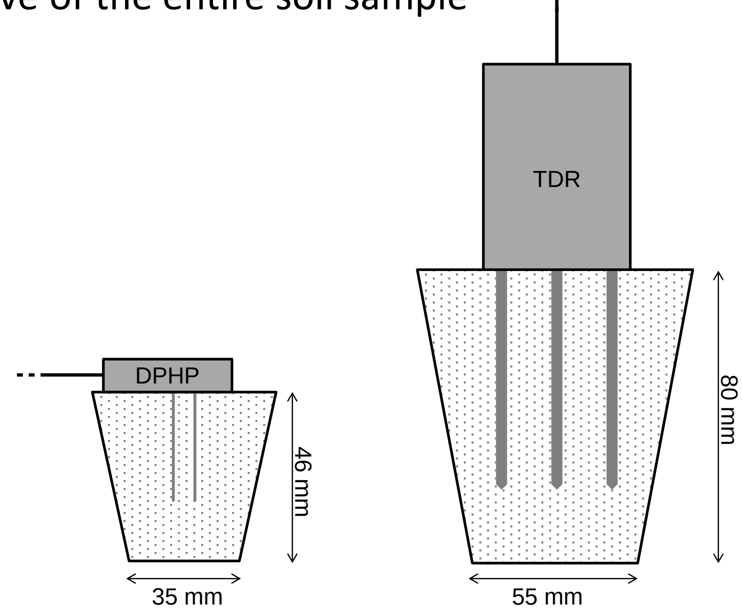
Apparent probe spacing is calibrated against measurement on medium with known thermal properties, such as water.

ΔT_m	t_m	q'	r	ρc	λ	$\varepsilon_{\rho c}$	ε_{λ}
0.595	63.1	82.8	0.005705	4003	0.55272	4.10	8.04
0.601	62.28	81.87	0.005654	3988	0.54871	4.45	8.71
0.604	63.28	81.87	0.005672	3944	0.53673	5.50	10.70
0.572	63.08	81.64	0.005741	4054	0.56709	2.87	5.65
0.573	64.58	81.42	0.005770	3995	0.55053	4.30	8.41
0.598	63.98	81.19	0.005691	3924	0.53131	5.98	11.60
0.585	63.48	80.5	0.005698	3967	0.54305	4.95	9.65

Laboratory test: soil moisture estimate

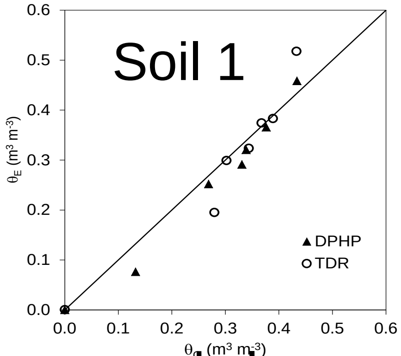
Experimental setup

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

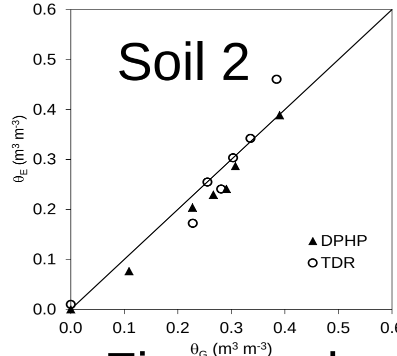


Laboratory test: soil moisture estimate

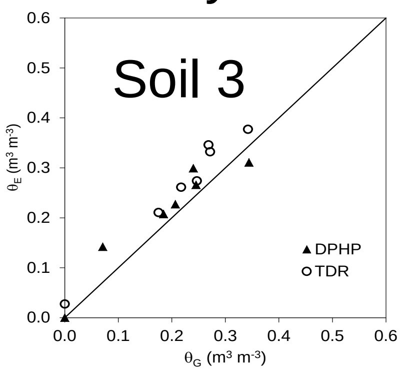
medium sand



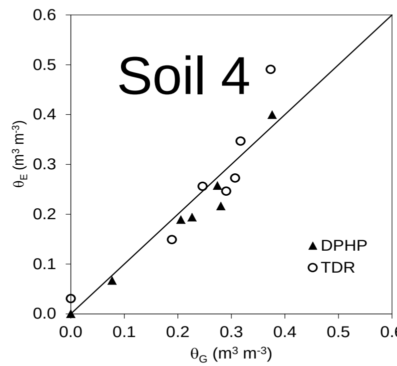
coarse sand



sandy loam



Fine sand



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

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

Conclusions

- The open hardware platform is good for self-building low cost device for soil thermal properties assessment.
- 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.

Future developments

- Develop a new version based on a more powerful board
- Implement different methods to estimate thermal parameters from temperature rise
- Include a GPS unit to log position of measurements during a field campaign

Thank you for your attention

This presentation available on www.ravazzani.it