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Feasibility of soil moisture monitoring with heated fiber optics

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[1] Accurate methods are needed to measure changing soil water content from meter to kilometer scales. Laboratory results demonstrate the feasibility of the heat pulse method implemented with fiber optic temperature sensing to obtain accurate distributed measurements of soil water content. A fiber optic cable with an electrically conductive armoring was buried in variably saturated sand and heated via electrical resistance to create thermal pulses monitored by observing the distributed Raman backscatter. A new and simple interpretation of heat data that takes advantage of the characteristics of fiber optic temperature measurements is presented. The accuracy of the soil water content measurements varied approximately linearly with water content. At volumetric moisture content of 0.05 m^3/m^3 the standard deviation of the readings was 0.001 m^3/m^3, and at 0.41 m^3/m^3 volumetric moisture content the standard deviation was 0.046 m^3/m^3. This uncertainty could be further reduced by averaging several heat pulse interrogations and through use of a higher-performance fiber optic sensing system.

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1. Introduction

[2] Soil water accumulation, storage, and depletion play a central role in the hydrologic cycle and the global water balance. Though many accurate methods are available for point measurement of soil water content, there are currently no precise in situ methods for measurement of soil water content from meter to kilometer scales. The goal of this article is to demonstrate the feasibility of the Active Heat pulse method with Fiber Optic temperature sensing (AHFO) to obtain precise, distributed measurements of soil water content across these spatial scales and over a broad range of soil water contents.

[3] The ability of fiber optic Distributed Temperature Sensing (DTS) systems to retrieve temperature readings each meter along fiber optic cables in excess of 10,000 m in length at high temporal frequency has afforded many important opportunities in environmental monitoring [e.g., *Selker et al.*, 2006a, 2006b; *Tyler et al.*, 2008, 2009; *Westhoff et al.*, 2007; *Freifeld et al.*, 2008]. Recently, *Steele-Dunne et al.* [2010] demonstrated the feasibility of using the thermal response to the diurnal temperature cycle of buried fiber optic cables for distributed measurements of soil thermal properties and soil moisture content. Unlike the AHFO method, the *Steele-Dunne et al.* [2010] method does not require an external source of energy. Nevertheless, its application remains challenging under conditions where the thermal response to the diurnal temperature cycle is not large enough to allow accurate estimation of soil moisture content (e.g., under dense vegetative canopy, at depths beyond the top few centimeters of the soil column, cloudy days, or other surface energy flux limited systems).

[4] The principle of temperature measurement along a fiber optic cable is based on the thermal sensitivity of the relative intensities of backscattered Raman Stokes and anti-Stokes photons that arise from collisions with electrons in the core of the glass fiber [see *Tyler et al.*, 2009]. A laser pulse, generated by the DTS unit, traversing a fiber optic cable will result in Raman backscatter at two frequencies, referred to as Stokes and anti-Stokes. The DTS quantifies the intensity of these backscattered photons and elapsed time between the pulse and the observed returned light. The intensity of the Stokes backscatter is largely independent of temperature, while anti-Stokes backscatter is strongly dependent on the temperature at the point where the scattering process occurred. Temperature can be inferred from the Stokes/anti-Stokes ratio. The computed temperature is attributed to the position along the cable from which the light was reflected, computed from the time of travel for the light [*Grattan and Sun*, 2000].

[5] Heat pulse methods are well established for the determination of soil thermal properties, soil water content and water movement. These methods usually apply a line source of energy to the soil with the resulting temperature fluctuation monitored by one or more parallel probes [*Bristow et al.*, 1994]. The rate of radial transmission of heat depends on the soil bulk density, mineralogy, particle shape, and, principally, soil water content [e.g., *Shiozawa and Campbell*, 1990]. Geometries where the thermal observations are colocated with the heated probe are referred to as

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single probe methods [*de Vries and Peck*, 1958; *Shiozawa and Campbell*, 1990; *Bristow et al.*, 1994]. Heat pulse methods have also been widely implemented in multiprobe geometries, with one or more sensing probes in proximity of the heat source [e.g., *Lubimova et al.*, 1961; *Jaeger*, 1965; *Larson*, 1988; *Campbell et al.*, 1991; *Bristow et al.*, 1993, 1994; *Heitman et al.*, 2003; *Ren et al.*, 2003, 2005].

[6] Many analytical and numerical methods have been developed for the interpretation of heat pulse experiments in soils. Typically, the solutions assume an infinitely small radius and infinitely long line source geometry. The thermal properties of soil are calculated from the heat pulse response via the solution of the radial heat conduction equation [*Carslaw and Jaeger*, 1959]. During heating, a pulse of duration t_0 (s) is applied to an infinite line heat source in a homogeneous isotropic medium which is taken to be at uniform initial temperature. The solution for the resulting temperature change following the commencement of heating that is given by [*de Vries and Peck*, 1958; *Shiozawa and Campbell*, 1990; *Bristow et al.*, 1994]

$$\Delta T(r,t) = -\frac{q'}{4\pi\kappa\rho c} Ei\left(\frac{-r^2}{4\kappa t}\right) \text{ for } 0 < t \le t_0 \tag{1}$$

and during cooling

$$\Delta T(r,t) = \frac{q'}{4\pi\kappa\rho c}\left[Ei\left(\frac{-r^2}{4\kappa(t-t_0)}\right) - Ei\left(\frac{-r^2}{4\kappa t}\right)\right] \text{ for } t > t_0, \tag{2}$$

where q' is the energy input per unit length per unit time (J m^{-1} s^{-1}), ρ is the density of the medium (kg m^{-3}), c is the specific heat of the medium (J kg^{-1} °C^{-1}), r is the distance from the line source (m), $\kappa = \lambda/\rho c$ is the thermal diffusivity (m^2 s^{-1}), λ is the thermal conductivity (W m^{-1} °C^{-1}), and *Ei* donates the exponential integral.

[7] In this implementation of the line source transient method, the radius of the heat source is assumed to be infinitely small. A correction factor can be added to the long time solution to account for the nonzero radius of the heat source. The validity of such a correction decreases with an increase of the probe radius [*Blackwell*, 1954]. To account for the finite dimensions of the cable, the cylindrical transient method can be used as described by *Jaeger* [1965] for a perfectly conducting cylinder with constant heat supply per unit length per unit time (q')

$$\Delta T = \frac{2q'\alpha^2}{\pi^3\lambda\rho c}\int_0^\infty \frac{\{1-\exp(-\tau u^2)\}du}{u^3\Delta(u)}, \tag{3}$$

where

$$\Delta(u) = \left[uJ_0(u) - \left(\alpha - hu^2\right)J_1(u)\right]^2 + \left[uY_0(u) - \left(\alpha - hu^2\right)Y_1(u)\right]^2, \tag{4}$$

$$\tau = \kappa t/a^2, \tag{5}$$

$$\alpha = 2\pi a^2 \rho c/S, \tag{6}$$

$$h = \lambda/aH, \tag{7}$$

with a being the heat source radius (m), S the heat capacity per unit length of the cylinder (J m^{-1} °C^{-1}), $1/H$ the thermal contact resistance per unit area between the perfect conductor and the surrounding material (m^2 °C W^{-1}), and $J_n(u)$ and $Y_n(u)$ the Bessel functions of u of order n of the first and second kind (dimensionless).

[8] Most of the existing heat pulse method literature focuses first on calculating λ and ρc from the thermal responses of the soil to a heat pulse. From these values, the soil moisture content is then inferred, since both λ and ρc of the soil monotonically increase with increasing water content. The well-known advantage of using the dual-probe method for soil water determination is that both thermal conductivity and volumetric heat capacity can be accurately obtained from a single measurement, while the single probe method is primarily sensitive to the thermal conductivity [e.g., *de Vries*, 1952, 1963; *Campbell*, 1985; *Kluitenberg et al.*, 1993; *Bristow et al.*, 1994]. The main advantage of obtaining the volumetric heat capacity of the soil is that it allows estimation of the change in soil water content without information on soil-specific thermal properties [*Bristow et al.*, 1993]. Some have tried to directly correlate soil moisture content to the temperature rise during heating [e.g., *Shaw and Baver*, 1940; *Youngs*, 1956]. A disadvantage of such methods is that a calibration curve that relates soil moisture content to temperature change is needed for each soil type, and for each probe design.

[9] Systems using more than two probes provide additional information (e.g., direction of flux), and are an active area of investigation [e.g., *Bristow et al.*, 2001; *Mori et al.*, 2003, 2005; *Hopmans et al.*, 2002; *Ren et al.*, 2000; *Green et al.*, 2003; *Kluitenberg et al.*, 2007]. Concerns regarding the accuracy of the different heat pulse methods remain, related to soil bulk density [*Tarara and Ham*, 1997], soil mineralogy [*Bristow*, 1998], contact resistance between the probe and the surrounding material [*Blackwell*, 1954], and temperature sensitivity [*Olmanson and Ochsner*, 2006].

[10] The use of actively heated fiber optic cable for observation of subsurface water movement has been demonstrated [e.g., *Perzlmaier et al.*, 2004, 2006; *Aufleger et al.*, 2005], though for determination of soil water content it was concluded that (1) the method could only distinguish qualitatively between dry, wet and saturated soils [*Perzlmaier et al.*, 2004, 2006; *Weiss*, 2003] and (2) small changes in soil water content could not be detected at levels above 6% volumetric water content [*Weiss*, 2003]. *Weiss* [2003] concluded that only with dramatic improvement of the signal-to-noise ratio of the DTS instrumentation could sufficiently accurate thermal conductivity be obtained by a DTS heat pulse method to quantify soil water content above this level.

[11] Although we agree that better DTS performance improves accuracy, here we argue that the DTS method can quantify moisture content more precisely than suggested previously by using a different approach to data interpretation. Both *Weiss* [2003] and *Perzlmaier et al.* [2004] used the long time approximation of either the line source or the cylindrical source transient methods to calculate the thermal conductivity of the soil, deriving the thermal conductivity from the slope and intercept of a line fit to the temperature response following an extended heat pulse. They then computed the moisture content using a calibration equation. Unfortunately, this fitting routine made use of data which varied little between moisture contents (particularly the fit-

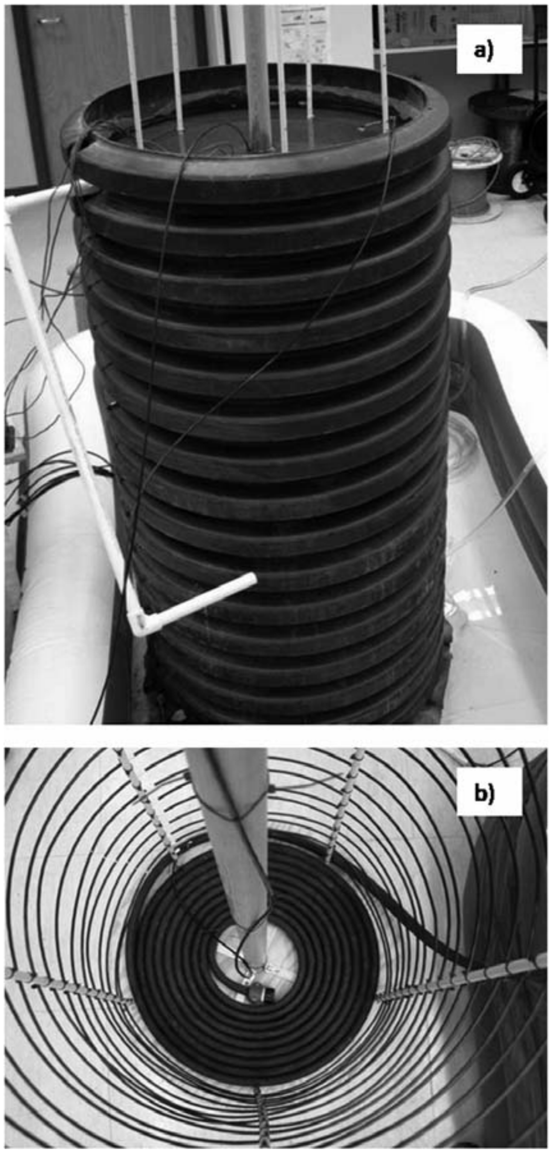

Figure 1. Images showing (a) the sand column and (b) the fiber optic section (in helical coils) before inserting into the sand column.

ted slope). Our approach was, in part, motivated by their data, where it was evident that though the slope of heating was rather insensitive to water content, the overall magnitude of the temperature change was quite sensitive to moisture content. This is partially due to the impact of the early time data that is not fully incorporated into the late time analysis. In addition, there is an intrinsic improvement in sensitivity found in integral methods compared to derivative (slope) approaches.

[12] Recent work has shown that more robust estimates of soil thermal properties are obtained using analyses that fit the entire data set of temperature change with time to a model [*Mortensen et al.*, 2006]. In this article we do not attempt to optimize the data interpretation, but rather demonstrate the power of a simple interpretation methodology that appears to make better use of information contained in the heat pulse data obtained with a DTS system. Opportunities for optimization of this method are manifold, and will be the topic of further research.

2. Materials and Methods

[13] We seek a response variable that monotonically varies with soil water content and is suited to the characteristics of the DTS measurement method. To this end, we propose quantifying the thermal response of the soil to the heat pulse in the form of cumulative temperature increase over a certain period of time

$$T_{cum} = \int_0^{t_0} \Delta T \, dt, \tag{8}$$

where T_{cum} is the cumulative temperature increase (°C.s) during the total time of integration t_0 (s), and ΔT is the DTS reported temperature change from the prepulse temperature (°C). T_{cum} is a function of the soil thermal properties. Higher heat capacity and higher thermal conductivity, both of which monotonically increase with soil water content (θ), increase the rate at which heat is conducted away from the probe and reduce the integral for sufficiently long heat pulses. Thus, there exists a 1 to 1 function relating T_{cum} to θ (under conditions where flow can be taken to be negligible) for a given soil, heating rate, integration time, and fiber optic cable characteristics.

[14] One may ask about the advantage of the integrated parameter compared to the maximum temperature increase approach described by *Shaw and Baver* [1940] and *Youngs* [1956]. The variance of the computed parameter is minimized by taking advantage of the fact that the DTS readings are fundamentally based upon cumulative photon counting. The standard deviation of DTS temperature measurements reduces with the square root of reading time [*Selker et al.*, 2006a]. This method allows use of relatively long reading times (photon integration) and low sampling rates. In fact, the value of T_{cum} is largely unaffected by sampling rate since the DTS will internally compute this integral as it reports lower time resolution data requiring, for example, a less expensive DTS recording instrument. It will be shown later that T_{cum} allows for more accurate estimation of soil water content than ΔT in our experimental setup.

[15] The high-speed DTS unit used in this experiment (Sensortran DTS 5100 M4) allows high frequency data collection for comparison of more traditional interpretations of the integral method. This DTS unit recorded temperature every 0.5 m along the fiber optic cable, with a spatial resolution of 1 m for each measurement. The average reading frequency was 0.2 Hz.

[16] A 0.61 m diameter sand column was supported by a 1.46 m tall smooth interior, corrugated exterior HDPE pipe (Figure 1). The bottom of the pipe was sealed with a rubber membrane, and an outlet was installed 0.05 m above the membrane seal. A 0.012 m diameter perforated hose was fitted to the inside of the drainage port and wound in a spiral laying flat on the bottom of the rubber seal to provide an easily controlled lower boundary condition. The drainage was actively controlled using a peristaltic pump.

[17] Within the column, 31.5 m of BruSteel (Brugg Cable, Brugg, Switzerland) fiber optic cable was distributed

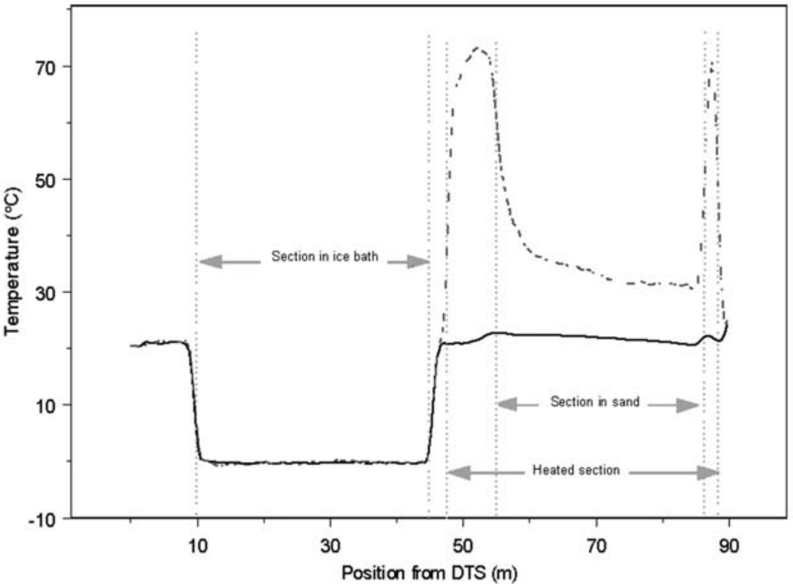

Figure 2. Temperature readings along the fiber optic cable before (solid line) and at the end (dashed line) of a 2 min, 20 W/m heat pulse for the drained soil column condition. The "before" temperature was obtained by averaging all readings during the 5 min directly proceeding the heat pulse start.

in a helicoidal geometry supported by five vertical 0.006 m diameter fiberglass rods (Figure 1). The 3.8×10^{-3} m outer diameter cable made twenty-one 0.48 m diameter helical coils, spaced 0.06 m vertically, starting 0.05 m from the bottom and ending at the surface of the sand (1.30 m from the bottom). The fiber optic cable employed was composed of two optical fibers encased in a central stainless steel capillary tube (OD 1.3×10^{-3} m / ID 1.07×10^{-3} m) surrounded by stainless steel strands (12 4.2×10^{-4} m OD stainless steel wires), all of which were enclosed in a 2×10^{-4} m thick nylon jacket. The metal components were used as an electrical resistance heater (0.365 Ω/m).

[18] Air-dried medium sand (d_{50} = 0.297 mm) was added in 0.30 m deep lifts with vibration of the entire column using a rubber mallet to settle the sand between lifts. No further settling was observed during the remainder of the experiment. The total depth of sand in the column was 1.30 m with 0.12 m of the HDPE pipe extending beyond the top of the sand.

[19] Computation of T_{cum} requires a precise value of the temperature before the start of the heat pulse. A 5 min DTS reading preceding each heat pulse was used as the baseline temperature. Thereafter, a 44.5 m section of the cable (including the section in the sand column) was heated by connecting the stainless steel windings at both ends of the heated section to a variable voltage AC current source (Staco® Variable Autotransformer Type 3PN1010). The drop in voltage along the 12 AWG copper connecting wires was ~0.1% of the total, and thus was assumed to be negligible. A digital timer with a precision of ±0.01% (THOMAS® TRACEABLE® Countdown Controller 97373E70) controlled the duration of the heat pulse. A wide range of combinations of power and time were tested, though in this article we discuss only the results of 2 min heat pulses at 20 W/m (120.2 VAC) which appeared to provide an appropriate balance of temperature response and duration relative to the DTS resolution. The measurements were repeated three times. T_{cum} was calculated using the data obtained over the entire heating period of 120 s. The temperature increase observed at the end of the heating period (ΔT_{120s}) will also be reported to compare its performance in predicting soil water content with that of T_{cum}. We chose to employ ΔT_{120s} because among all values of ΔT for heating and cooling it had the highest signal-to-noise ratio. A reference temperature reading was obtained from a 33 m coil of fiber optic cable kept in an ice-filled water bath (0°C) (Figure 2).

[20] DTS readings were taken in dry, saturated and drained conditions. The drained condition was obtained one month after establishing the water table at 0.4 m above the bottom. Following the final DTS measurements in the drained column, triplicate volumetric samples were obtained from eight depths between the sand surface and the water table (spanning 0.9 m) for calibration.

3. Results and Discussions

[21] Volumetric soil moisture content of samples taken from the drained column varied from 4% to 41% (saturated), with a sharp transition 0.3 m above the water table, typical of sands (Figure 3). Repeatable, distinct values of T_{cum} were obtained up to saturation (Figure 3). The slope in the $\theta - T_{cum}$ and $\theta - \Delta T_{120s}$ relationships decreased with water content (Figures 4 and 5), suggesting lower sensitivity at higher water contents, as found in previous studies [e.g., *Weiss*, 2003].

[22] To estimate the error in soil water content (θ) obtained from T_{cum}, a function $f(\theta)$ was fitted to the T_{cum} versus θ data using least squares regression (Figure 4). For each value of θ, the estimated error (σ_θ) was calculated as

$$\sigma_\theta = \frac{\sigma_{T_{cum}}}{\left|\frac{df(\theta)}{d\theta}\right|}, \tag{9}$$

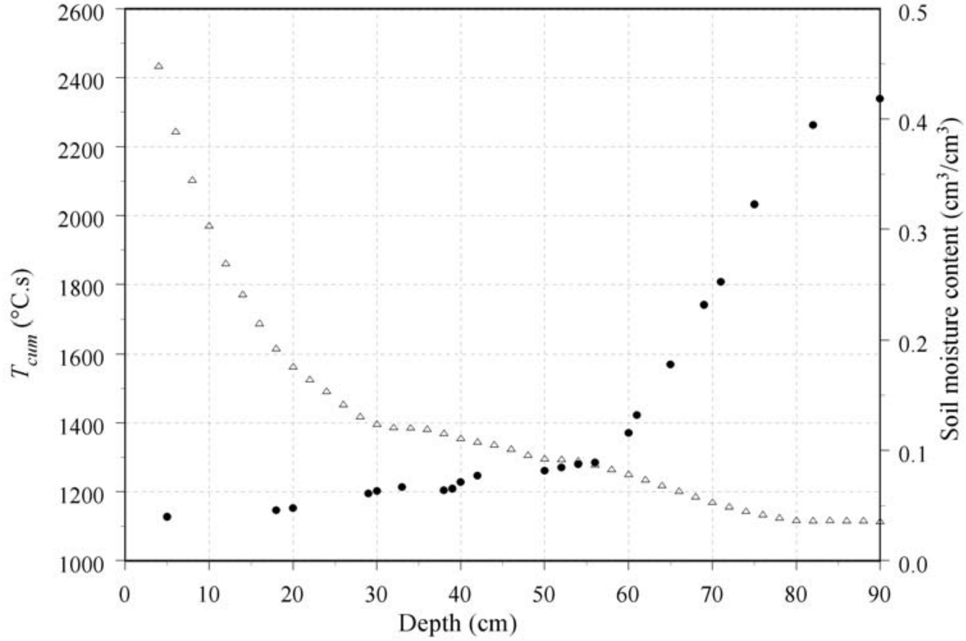

Figure 3. Measured soil water content (circles) and cumulative temperature increase (triangles) as function of depth for a 2 min, 20 W/m heat pulse.

where $\sigma_{T_{cum}}$ is the standard deviation of T_{cum}, $\frac{df(\theta)}{d\theta}$ is the local slope of the T_{cum} response evaluated at θ. In general, the standard deviation of DTS-measured temperature depends on the distance from the DTS recording unit, increasing with light loss as it potentially travels kilometers of distance from the unit [e.g., *Tyler et al.*, 2009]. However, over shorter cable distances, such as the 50 m span employed here, this effect is negligible. Therefore, the standard deviation of T_{cum}, $\sigma_{T_{cum}}$, should only depend on the performance of the DTS system. In this experiment, $\sigma_{T_{cum}}$ was computed as the aver-

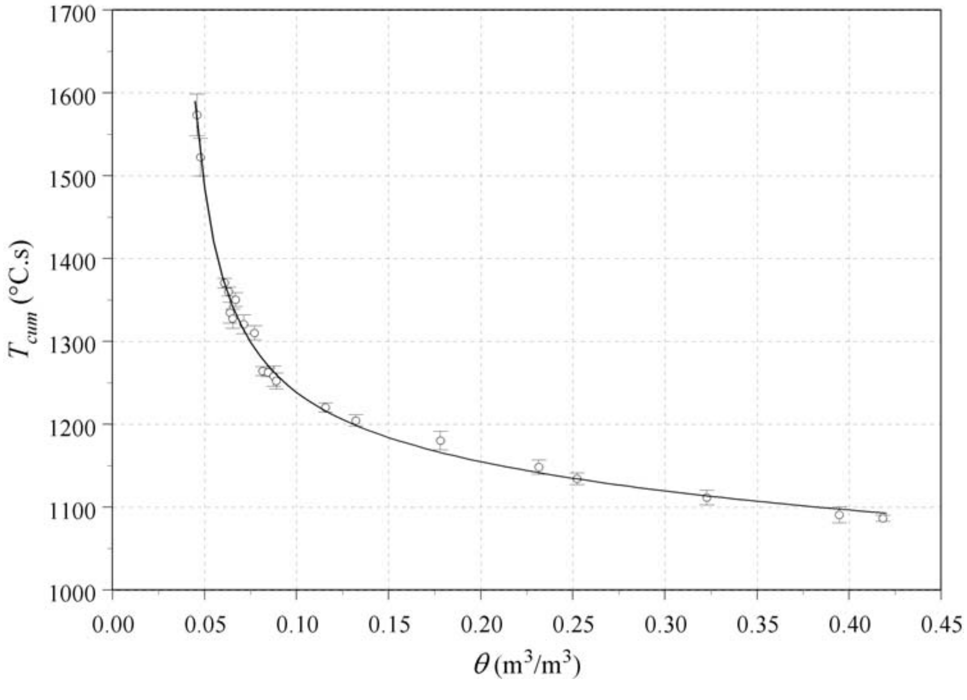

Figure 4. Average cumulative temperature increase (T_{cum}) integrated over 120 s as function of soil water content (θ) for three 2 min, 20 W/m heat pulses and fitted function. For each soil water content value, the error bars are obtained from the standard deviation of three repetitions. The R^2 of the fitted function is 0.994.

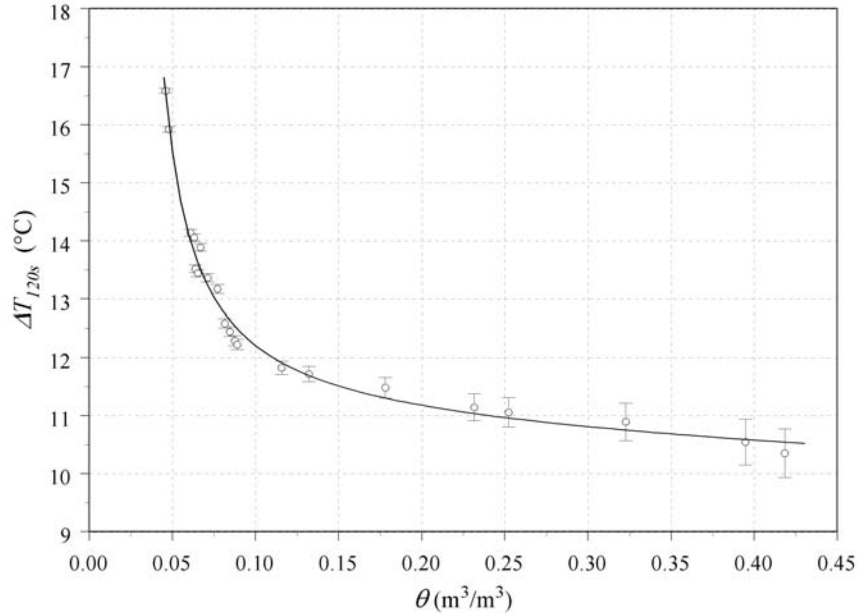

Figure 5. Average temperature increase at 120 s (ΔT_{120s}) as function of soil water content (θ) for three 2 min, 20 W/m heat pulses and fitted function. For each soil water content value, the error bars are obtained from the standard deviation of three repetitions. The R^2 of the fitted function is 0.987.

age of all standard deviations of T_{cum} observed along the 30 m cable section in the sand column. The same method was employed to estimate the error in soil water content obtained from ΔT_{120s}. The error analysis shows that σ_θ obtained from either T_{cum} or ΔT_{120s} increased approximately linearly with soil water content (Figure 6). As expected, the error in soil water content obtained from T_{cum} was much smaller than that obtained from ΔT_{120s} (Figure 6). This error could be further reduced by increasing the signal-to-noise ratio, which could be accomplished by averaging several heat pulse results, using a more precise DTS unit, increasing the heating intensity, or increasing the duration of heating.

[23] A large heat pulse could cause water to evaporate and/or diffuse away from the cable [*Farouki*, 1986]. To avoid this, and to minimize the energy required to complete

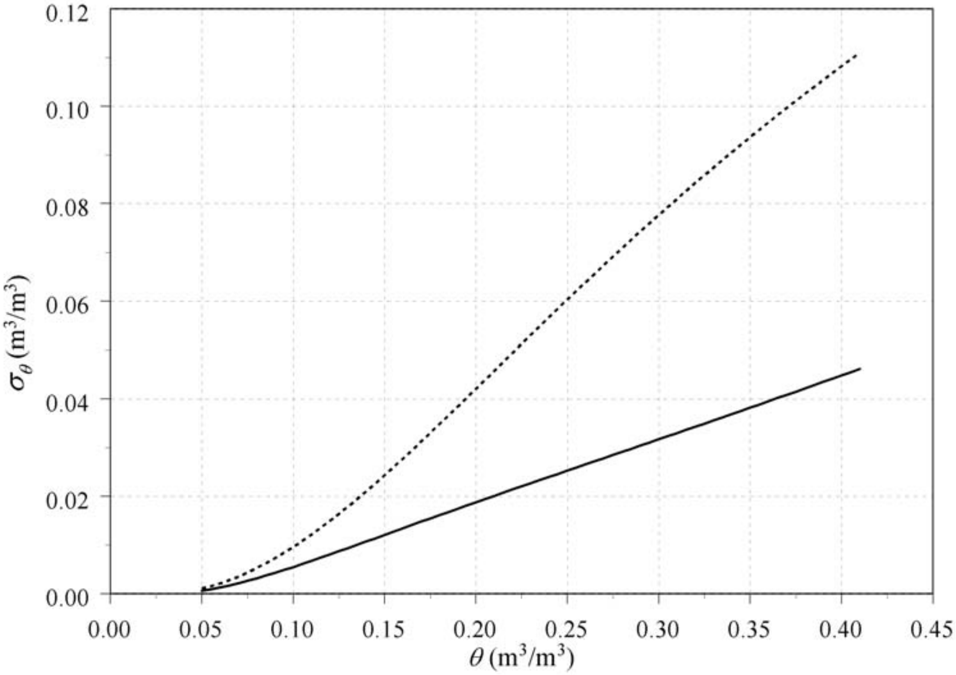

Figure 6. Calculated error (σ_θ) in soil water content derived from T_{cum} (solid line) and from ΔT_{120s} (dashed line) as function of soil water content (θ).

a measurement, it is desirable to reduce both the magnitude and duration of temperature increase. An important advantage of the integral method is that a relatively good estimate of soil water content can be obtained with a brief heat pulse. In this experiment, the maximum cable temperature never exceeded 17°C over the ambient soil temperature (Figure 5). The injected energy was less than 2.4 kJ/m, compared to the 11.7 kJ/m for *Weiss* [2003] and greater than the 72 kJ/m employed by *Perzlmaier et al.* [2004]. The much shorter heating interval employed here (120 s), compared to 626 s used by *Weiss* [2003] and 7200 s by *Perzlmaier et al.* [2004], greatly reduces the potential for such disturbance. That said, *Weiss* [2003] indicated that his approach did not give rise to water displacement, and our experiment showed no change in T_{cum} with replication, suggesting there were no significant distortions due to the heat pulse measurements. Sequential measurements did not show persistent cumulative heating in our experiments, but this would ultimately provide a practical limit to the feasible sampling frequency using this method. Fortunately, this cumulative heating can easily be measured with DTS.

[24] Currently marketed DTS systems have both a tenfold higher speed of reading performance and four times better spatial resolution than that employed here. The magnitude of the heat pulse required to obtain a particular level of precision is scaled linearly with reading speed, thus we have by no means explored the instrumentation limitations on accuracy or energetic requirements of the DTS approach.

[25] While the laboratory results are encouraging, field measurements of soil water content using the DTS-based heat pulse method are expected to bring additional sources of uncertainty. Expected primary sources of error include poor contact between the probe and soil, and the spatial variability of soil thermal properties.

[26] Finally, in addition to varying with moisture content, T_{cum} is expected to be a function of the convective flow of water around the heated cable. An increase in convective flow will further increase the rate at which heat is dissipated away from the probe and thereby reduce T_{cum}. Thus, this method has the potential to not only detect soil water content but also to monitor water fluxes in saturated soils, as demonstrated by *Perzlmaier et al.* [2004], with long heated durations. The ability to use shorter pulses based on the method proposed here allows greater separation between measurements of moisture content and flux.

4. Conclusion

[27] We have shown that the heat pulse method using coaxial heating and a DTS system is feasible for determination of soil water content across a much broader range of values than previously reported. This result was found by using a response metric that has not been previously employed: the time integral of temperature deviation. This strategy is especially appropriate to the DTS method wherein precision of temperature reporting is a direct function of the interval of photon integration. Though we have used high temporal resolution in the DTS measurements, this method can provide the same level of precision with less expensive, slower DTS instruments since the data can be integrated in time for analysis. Further, using more sensitive DTS systems, the technique could be more accurate and use shorter, lower energy heat pulses which may be of importance in remote application of the method.

[28] While this study demonstrates feasibility, additional work is required to develop optimal heating and interpretation strategies for DTS-based heat pulse methods, building upon the rich literature related to needle heat pulse systems. The key finding of this work is to confirm the potential to employ DTS systems to monitor soil water content at temporal resolutions well under one hour and at high spatial resolution (≤1 m). In principle, this DTS method could monitor soil moisture along cables exceeding 10,000 m in extent. This would allow for concurrent observation of thousands of adjacent locations, which will likely provide new insights into the spatial structure of infiltration and evaporation. Such measurements could be transformative in our understanding of soil hydrology in natural and managed systems at field and watershed scales. Many challenges remain (e.g., installation in the presence of stones and roots), calling for significant further effort in developing this methodology. For example, we presented only results from a single-probe DTS approach, though multiple probe approaches using DTS are expected to be of utility just as they have been in other soil heat pulse applications.

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