1   **Full title: A Distributed Heat Pulse Sensor Network for Thermo-Hydraulic Monitoring of**

2   **the Soil Subsurface**

3   **Abbreviated Title: Distributed Heat Pulse Sensor Network**

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12   **Abstract:**

13   Fibre optic distributed temperature sensing (DTS) is used increasingly for environmental monitoring

14   and subsurface characterisation. Combined with heating of metal elements embedded within the

15   fibre optic cable, the temperature response of the soil provides valuable information from which soil

16   parameters such as thermal conductivity and soil moisture can be derived at high spatial and

17   temporal resolution, and over long distances.

18   In this manuscript, we present a novel Active Distributed Temperature Sensing (A-DTS) system and

19   its application to characterise spatial and temporal dynamics in soil thermal conductivity along a

20   recently forested hillslope in Central England, UK. Compared to conventional techniques (needles

21   prob surveys), A-DTS provided values with similar spread though lower on average. The larger

22   number of measurement points that A-DTS provides at higher spatial and temporal resolutions, the

23   ability to repeat surveys under different meteorological/hydrological conditions allows for a more

24   detailed examination of the spatial and temporal variability of thermal conductivities at the study

25   site. Although system deployment time and costs are higher than with needle probes, A-DTS can be

26   extremely appealing to applications requiring (1) long term monitoring, (2) at high temporal

27   repeatability, (3) over long (km) distances and with (4) minimum soil disturbance, rather than one-

28   off spatial surveys.

29

Background

Detailed knowledge of the ground's thermal properties is essential for process understanding in many areas in engineering, agronomy, and environmental and soil sciences. In recent years, considerable efforts have been made to develop methodologies for determining thermal properties of soils and rocks. One key parameter is thermal conductivity, which is the capacity of a material to conduct heat. Good knowledge of the thermal conductivity term is required in a variety of applications, e.g. to design ground source heating/ cooling systems, solar thermal storage, or underground cable installations.

Thermal conductivity is controlled by inherent properties of the geological substrate (texture, mineral composition) and its transient properties (moisture content, compaction, bulk density and porosity). Values of thermal conductivity can be calculated from the soil composition using soil physical models (Côté and Konrad, 2005; Lu et al., 2007) and can also be obtained using laboratory sample measurements (e.g. Clarke et al. 2008). These methods either require high-resolution soil data sets (currently not available for the UK) or they alter important soil parameters, such as the in-situ compaction and bulk density, and hence change the soil thermal properties (e.g. Kersten, 1949).

In-situ measurements of thermal conductivity are thus preferable. These can be made by observing changes in soil temperature in response to natural (i.e. diurnal / seasonal) temperature signal (e.g., Busby 2015) or to actively-induced heat flows. This principle is used in classic single-needle heat pulse probes (Bristow et al. 1994; Campbell et al. 1991) , which use small-diameter thermal needles with a typical needle length of 0.03–0.10 m (e.g. Decagon Devices 2016; Hukseflux 2017) to determine soil thermal properties. These measurements are usually only representative of a relatively small cylinder (0.1 – 0.3 m diameter) of soil around the probe (Decagon Devices 2016; Hukseflux 2017). A representative assessment of a site's 'bulk' soil conductivity thus requires a significant number of measurements across a site. King et al. (2012), for example, suggest 12–16 determinations for sites of up to 100 m × 40 m in dimension. However, the measured thermal

57   conductivities are still only valid at a particular time as these near surface thermal properties are

58   strongly affected by the seasonal variation in soil moisture regime.

59   Thermal response tests (TRT) are an active, borehole-based method that is widely used in the design

60   of vertical borehole heat exchanger (BHE) systems (e.g. Banks et al., 2013). The tests provides a

61   value of ground bulk thermal conductivity and are considered to be accurate to within 10%

62   (Signorelli et al., 2007). Fibre-optic distributed temperature sensing (DTS) has been used to

63   characterize the vertical distribution of thermal properties within the vertical borehole during a TRT

64   (e.g., Fujii et al. 2009; McDaniel et al. 2018). However, there is at present no equivalent to the

65   vertical borehole TRT for horizontal systems.

66   Active Distributed Temperature Sensing (A-DTS) employs a similar principle to needle probes, i.e.

67   electrical heating of a fibre-optic (FO) cable while measuring the temperature response along the

68   cable to determine the thermal properties of the surrounding soil. The advantage of this method

69   over the needle heat pulse probe is that it enables the estimation of thermal property distributions

70   along long profiles (e.g. in the order of several kilometres) at spatial resolutions of up to 0.25m.

71   Measurements are easily repeatable; hence the method can also be used to monitor temporal

72   changes in transient soil properties. The concept underlying this A-DTS method is well-established

73   and was successfully proven in controlled laboratory condition, i.e. for artificial systems consisting of

74   homogeneous, bare soils of known mineralogy and soil moisture content (Cao et al. 2015; Ciocca et

75   al. 2012). However, applicability of the method has yet to be demonstrated for actual field –based

76   conditions, which usually are far more complex than those set up in laboratories, with soils

77   consisting of a heterogeneous mix of particle sizes and textures, containing different mineral

78   components, organic matter and water contents, and being covered by different types of vegetation.

79   In this study, horizontal fibre optic cable loops are deployed at a recently-forested hillslope to test

80   the ability of A-DTS to estimate soil thermal conductivities in natural, heterogeneous field settings

81   where distributions of soil properties, including moisture content, organic matter content and

82   mineralogical composition are largely variable and unknown. As calibration of the method in a

83   medium of known conductivity is difficult within such complex field settings, we perform a

84   comparison with point measurements made with calibrated thermal needle probes as a way of

85   assessing the validity of our results. This manuscript presents first results from this field application

86   of A-DTS, evaluates results against established needle probe techniques and identifies areas where

87   further study is needed to better understand and improve the performance of the proposed

88   method.

Study Site

90   The study site is located in Staffordshire, United Kingdom (Figure 1a), adjacent to the Birmingham

91   Institute of Forest Research (BIFOR) experimental site at Mill Haft (52°47'59"N, 2°18'17"W). The local

92   geology is dominated by the Permo-Triassic Sherwood Sandstone formation, which at the study site,

93   is covered by 10-15 m of superficial deposits, consisting of diamicton / boulder clay (glacial till) and

94   glaciofluvial sand and gravels (Figure 1b). Diamicton is an unsorted, unstratified deposit consisting

95   mostly of a clay and silty clay-dominated matrix with embedded particles that range in size from clay

96   to boulders. It is variable in colour and generally reflects the nature of the source rock material

97   (British Geological Survey, 2018) . Grain size variability at the study slope is illustrated in Figure 2,

98   picturing sandy clay (Figure 2b) and boulders (Figure 2c) that were observed in dug pitches at the

99   instrumented slope. Particle size analysis conducted in January 2015 on soil cores that were

100   extracted from up to 1m depth at different locations across the study site confirmed a high clay

101   content (~30% particles <0.063mm) and the presence of small quantities (<10%) of coarser material

102   >2mm (Ciocca et al., 2015).

103   Current land use at the site consists of a forested plantation along the hillslope, which has been

104   planted in spring 2014 with rows of deciduous saplings (primarily English oak, *Quercus robur*, and

105   sycamore, *Acer pseudoplatanus*), at distances of approximately 1 m between saplings and 1.5 m

106   between rows. Prior to that, the site was used for arable farming. The mean annual air temperature

107   at the study site is 9°C and mean annual precipitation is 690 mm (Norby et al., 2016).

Theoretical background

108

Measurement principle and key equations

109

110   Various methods exist for inferring thermal properties of soils from the temperature response to

111   heating. These are generally based on the solution of the heat conduction equation for a line heat

112   source (or cylindrical heat source) buried in a homogeneous medium – which is the basis for the

113   widely used 'probe method' (e.g. Farouki, 1981; Carslaw and Jaeger, 1959). The simplest

114   approximation is to consider the probe as an infinitely long line source of infinitesimal radius, which

115   is uniformly heated and transfers heat energy into a homogeneous and isotropic volume of soil. Such

116   approximation is also valid (within a certain time range) for probes that represent a cylindrical heat

117   source of finite length and finite thickness.

118   The measurement principle is as follows: (1) An electrical current is applied to the heating elements

119   in the FO cable (or thermal probe) to generate heat (Joule heating) at constant power Q (W/m)

120   (expressed as power per unit length of heater). (2) The change in temperature ΔT (K) is measured as

121   a function of time t (s) during both the heating phase, that starts when the heater is switched on

122   (t=0) and the cooling phase, that starts when the heater is switched off after a time t_H (s), which is

123   the heat pulse duration. (Note that both, heating and cooling phase can be used independently to

124   estimate the thermal conductivity (e.g. Bristow et al., 1994)). (3) During electrical heating, following

125   a transient period, an asymptotic stage is attained where the measured temperature change ΔT (K)

126   approximates a log-linear function, which is directly proportional to the power input Q (W/m) and

127   inversely related to the soil thermal conductivity λ (W/m K) (Bristow et al.,1994) according to:

128
$$\Delta T \approx \left(\frac{Q}{4\pi\lambda}\right)(\ln t) + b$$

129   (Equation 1)

130   where *b* is a constant. (4) Plotting ΔT (K) as function of *ln(t)*, the soil thermal conductivity can be

131   calculated from the slope of the straight line, once the log-linearity of ΔT (K) (i.e., the asymptotic

132   regime) is attained (Figure 6). The time necessary to reach the asymptotic regime depends on the

133   duration of the transient period, which we refer to in this paper as the *pre-asymptotic stage*.

134   During the pre-asymptotic stage, the measured temperatures are influenced by the non-ideal

135   thermal characteristics of the probe and the contact resistance between the probe and the soil

136   (Shiozawa and Campbell 1990). This causes temperatures to increase more rapidly than predicted by

137   the log-linear trend in Equation 1 (dotted line in Figure 6). Pre-asymptotic data are generally

138   excluded from the analysis. However, Van der Held and Van Drunen (1949) demonstrated that the

139   introduction of a time correction factor t_0 into Equation 1 can partially compensate for (i) finite

140   thickness of the probe, (ii) thermal contact resistance probe-soil and also (iii) the temporal gap

141   between the beginning of the electrical heating (t=0) and the nearest temperature measurement,

142   e.g. in systems where temperature cannot be measured at high sampling rate (e.g. every second or

143   faster). Incorporating t_0 into Equation 1 gives (de Vries, 1952; Shiozawa and Campbell 1990)

144
$$\Delta T(t) \approx \frac{Q}{4\pi\lambda}\ln(t + t_0)$$

145   Equation 2

146   Equation 2 approximates the temperature response to the heating not only during the asymptotic

147   stage (as Equation 1), but already during the pre-asymptotic stage, with a discrepancy from the

148   analytical solution within 5% (Van der Held and Van Drunen, 1949). Typically, the time correction

149   factor t_0 is not known a priori and must therefore be determined from complex laboratory

150   measurements, or estimated from Equation 2 together with the thermal conductivity by means of

151   non-linear regression.

152   When the pre-asymptotic stage is short, the general approach is to exclude pre-asymptotic data

153   from the analysis and to estimate thermal conductivities by regressing measured temperature

154 change from the later stages of heating (i.e. the asymptotic stage when data progressively reflect the

155 average characteristics of the surrounding soil (Shiozawa and Campbell 1990)) against *ln(t)* (Bristow

156 et al. 1993), according to Equation 1. For thermal needle probe applications, the duration of this pre-

157 asymptotic period is estimated in good approximation as $5r^2/\alpha$ (with r = radius of probe and α = soil

158 thermal diffusivity) (Hukseflux 2017); typical values are around 70s (King et al. 2012). In A-DTS

159 applications, however, the heated probe (i.e. the FO cable) presents a thicker and more thermally

160 insulated configuration, hence the heating periods required to reach expected asymptotic solution

161 can be much longer. Values of > 120 s (Ciocca et al. 2012) can be expected, especially in dry soils,

162 because of the high thermal contact resistance. Increasing the heat pulse duration to > 1000s (e.g. as

163 a way of obtaining a long time window of asymptotic data) is not possible because axial heat

164 diffusion within the cable during continuous heating would eventually lead to a noticeable departure

165 from the asymptotic log-linear behaviour as the temperature approaches steady state , instead of

166 following of a monotonic increase with time (Weiss, 2003). Therefore, the possibility to use pre-

167 asymptotic data becomes a critical factor when analysing data from A-DTS applications. From the

168 above discussion, it is obvious that heating strategies, i.e. the applied power and duration of heating

169 periods, are an important aspect of designing measurement programmes for needle probe surveys

170 as well as A-DTS campaigns. A balance must be struck between obtaining meaningful information

171 from both pre-asymptotic and asymptotic stages, avoiding axial heat diffusion and minimising the

172 effects of heating on the soils conditions (i.e. water displacement due to excessive heating (Weiss,

173 2003) or the development of free convection under conditions of near saturation (Sayde et al. 2014).

174

175 ## Active Distributed Temperature Sensing (A-DTS) method

176 Distributed Temperature Sensing (DTS) is used by a wide range of applications in environmental

177 monitoring (e.g. Selker et al. 2006) and building observations (e.g. Ferdinand et al. 2014). It utilises

178 the interaction of laser light with the silica core of a fibre-optic cable and applies time-domain

179 reflectometry to determine soil temperature at discrete sections along the cable. During a typical

180 measurement campaign, the DTS instrument launches short laser pulses at high temporal

181 frequencies along the optical fibre, and measures the backscatter that is generated as the light

182 propagates along the cable. The Raman component of the scattering is temperature-dependent and

183 is used to calculate temperature profiles within the optical fibre (Gratton and Meggitt, 2000; Rose et

184 al., 2013; J. S. Selker et al., 2006). Active Distributed Temperature Sensing (A-DTS), also known as

185 Actively Heated Fibre Optics (AHFO) techniques combine DTS measurements with a heat source, i.e.

186 a metal conductors, embedded within the structure of the cable (Figure 5). Directing an electrical

187 current (e.g. controlled by a variator or a Heat Pulse Control Unit – HPCU) through the metal

188 conductor provides a distributed heat source, which is activated at the same time as temperatures

189 are measured along the FO cable. These temperature data, measured during heating and/or cooling

190 of the cable, reflect the combined efficiency of heat dissipation in the cable and the surrounding

191 medium, allowing spatially distributed estimates of the surrounding thermophysical properties or

192 fluid fluxes to be derived (Aufleger et al., 2000; Bense et al., 2016; Perzlmaier et al., 2006,

193 2004)(Striegl and Loheide, 2012; Weiss, 2003), (Gil-Rodríguez et al., 2012).

194 Similar to thermal needle probes, the heated fibre optic cable can be conceptualized as a single

195 probe and approximated as a cylindrical heat source of finite length (equal to the length of each

196 spatial sample along the FO) and finite radius. The conductive cores represent the heating elements

197 and the optical fibre the distributed thermometer adjacent to the source (Figure 5). Previous studies

198 analyzed each spatial sample using Equation 1 (e.g. Weiss, 2003). Ciocca et al., (2012) showed that

199 the long heating time required by A-DTS systems to attain the asymptotic stage (up to several

200 minutes in dry soils) leaves only a limited time window for obtaining suitable data. To enable use of

201 pre-asymptotic data, they introduced an iterative method for identifying a threshold time $t>0$ during

202 the pre-asymptotic stage after which Equation 2 becomes applicable. The theory is detailed in Ciocca

203 et al., (2012) for both the heating and the cooling phase, and it was successfully applied to calculate

204 distributed thermal conductivities from the cooling phase of A-DTS data collected in a bare, loamy

205 soil after application of a 120s heat pulse interval. This short pulse duration, however, prevented the

206 application of the modified solution to the heating phase.

207 In this study, heating times of 900s are applied during A-DTS tests (see Methodology section) to

208 enable the application of the method suggested by Ciocca et al. (2012) to the heating phase data.

Thermal needle probe method

210 Thermal needle probe systems are sensor –systems for measuring thermal conductivity and thermal

211 resistivity in sediments and soils. They consist of a probe ("needle") which incorporates a heating

212 wire and a temperature senor, and a control /read out unit. Underlying measurement principles and

213 assumptions are based on the transient line-source theory (Carslaw and Jaeger 1959).

214 Measurements are taken by inserting the probe into the soil at the desired location / depth and

215 allowing needle to equilibrate with the surrounding soil temperature. Once equilibrated, a constant

216 heat flux is generated by applying a voltage to the heating wire in the probe, and the change in

217 temperature ΔT (K) at the probe is measured as a function of time t (s) since start of heating and

218 thermal conductivity is then calculated from the gradient of Equation 1. In these systems, early time

219 data are excluded from the calculation, e.g. the KD2Pro only uses the last 2/3 of collected data

220 (Decagon Devices 2016) while the FTN02 sensor uses the last 1/2 of the measurement cycle for its

221 initial calculations (Hukseflux 2017). This means that effects related to thermal properties of the

222 probe and contact resistance, which influence data collected during early time of heating, can be

223 ignored.

224

Methodology

Active DTS survey

227 *Site installation and set up:*

228 Active fibre optic cable loops were installed at the hill slope (Figure 1), centrally between two

229 adjacent rows of trees (slope 1 and slope 2 in Figure 1) and at three different depths (0.40 m, 0.25 m

230 and 0.10 m) below the surface. An armoured, multi-component cable (manufactured by Berk-Tek

231 Inc., US) was used in this study, containing two 18 AWG (America Wire Gauges) insulated copper

232 conductors (electrical resistance = 21 Ω/km per conductor) (for heating) and two Multi Mode

233 50/125µm optical fibres (MMF) (for measuring temperature) (Figure 4). The cable was selected for

234 its stability and safety of deployment in field environments. It has an outer diameter (OD) of 0.0077

235 m and a composite structure (Figure 4). For installation of the FO cables, a soil trench of 500 m [L] x

236 0.40 m [D] x 0.10 m [W] was excavated in July 2015 (Figure 3a), by means of a hydraulic tracked

237 trencher (Barreto Manufacturing, US). The first cable was laid inside the trench, at 0.40 m depth

238 from the soil surface, and the trench was then carefully backfilled with the previously excavated soils

239 up to a depth of 0.25 m, repeatedly compacting the soil tapping with a flat hammer head and

240 checking for the proper depth before a second fibre optic cable was laid. The operation was

241 repeated at 0.10 m depth for a total of 1,500 m of optical cable buried; the trench was then

242 backfilled with soil (Figure 3b). Conductors for each cable emerging from the trench were wired in

243 parallel and connected to three manual electrical switches in order to lower the total electrical

244 resistance of each cable to 10.5 Ω/km, and to permit the heating of the cable at a selected depth.

245 In addition, 15 soil moisture capacitance-based point probes (5-TM, Decagon devices, US) were

246 installed at depths of 0.10 m, 0.25 m and 0.40 m below the soil surface at five different locations

247 along the cable (Figure 1), three at slope 1 (R1, R2, R3 in Figure 1b) and two at slope 2 (L1, L2 in

248 Figure 1b). The probes were connected to battery-powered data loggers (Em50, Decagon Devices,

249 US) for continuous acquisition of soil moisture data at 10 minutes' intervals. The point-capacitance-

250 probe at location R1 and 0.10 m depth developed technical problems during the monitoring period

251 and was therefore not included in the analysis. For the period 01- Jul-2015 – 31-Dec-2015, daily

252 precipitation data were collected from a Met Office tipping bucket (resolution of 0.2 mm) rain gauge

253 (ID 55915, Met-Office, 2017) in approximately 2.12 km distance south-east of the field site. From

254   January 2016, precipitation was measured at the Mill Haft site, using a tipping bucket (resolution of

255   0.2 mm). Soil moisture measurements and rainfall data for the study period are shown in Figure 4.

256   *Power supply and instrumentation:* The power source was a 7kW, 230V, 32Amps petrol generator

257   (Briggs and Stratton, US). The MMF from all the cable ends were spliced together in three

258   consecutive duplex configurations (e.g. (Hausner et al., 2011; Krause and Blume, 2013)), to form a

259   unique optical path integrating signals sensed in both forward and reverse direction within one

260   single DTS measurement. The A-DTS tests were performed using three DTS instruments (Silixa Ltd,

261   Elstree, UK: (a) a XT-DTS™, 5 km range, 0.25 m sampling resolution; (b) an Ultima-S™, 5 km range

262   and 0.25 m sampling resolution and (c) an Ultima-M™, 10 km range and 0.25 m sampling resolution.

263   The different DTS were set to measure in double-ended configuration (i.e. measurements are

264   performed in sequence half of the time in one direction and half in the opposite, and the

265   temperature is obtained by combining raw data from the two directions) (e.g. Van de Giesen et al.,

266   2012). Double-ended configuration have proved particularly effective to compensate for installation-

267   related drifts in the DTS readings, as for instance introduced by the presence of multiple fusion

268   splices (e.g. van de Giesen et al., 2012). Double-ended measurements also provide the advantage of

269   a temperature resolution that follows a parabolic profile (e.g. van de Giesen et al., 2012), i.e. the

270   resolution is poorer at the near and far ends (i.e. where cable ends are connected to the DTS

271   interrogator) and is highest towards the mid-range (i.e. the slope sections).

272   *DTS Measurement campaigns*: A total of four A-DTS tests (23 October 2015, 08 June 2016, 09 June

273   2016 and 25 October 2016) were performed as part of this study. Heating was applied to the cable

274   sections buried in the ground with each individual depth being tested consecutively. The desired

275   electrical current was conveyed to the cables via a Heat Pulse Control Unit (HPCU) (Silixa Ltd, Elstree,

276   UK), which has an embedded high precision power controller (MicroFusion, Control Concepts, US).

277

278   The cables were heated sequentially for 900 s, starting with the deepest cable at 0.40 m. Power

279   densities between 3.3W m^{-1} and 5.0W m^{-1} (in agreement with Striegl and Loheide, 2012) were

280   applied (Table 1) with negligible fluctuations allowed by the HPCU (<1%). Despite the higher rating,

281   the generator could only provide a continuous supply of up to 2.5kW, preventing the application of

282   higher pulse intensities (e.g., > 20 W m^{-1}) as done in previous studies (Ciocca et al., 2012; Sayde et

283   al., 2010). The short heating time (compared for instance to TRT tests lasting days), low power

284   densities applied, and the thermal insulation of the cable, limited the radial thermal footprint to

285   about 0.03 metres (Weiss, 2003) around each cable. This allowed to safely apply a short spacing

286   between the three cable layers to allow investigating thermal conductivity variations at the very top-

287   soil, where many thermal and hydrological processes take place.

288

289   _Data processing and thermal conductivity calculations:_ Spatial and temporal interpolation using a

290   piecewise cubic polynomial interpolant (function 'spline', Matlab®) was applied to standardize all

291   data to 0.25 m spatial and 10 s temporal sampling resolution, respectively. The mirrored

292   measurements at each depth were averaged to increase the temperature resolution along the cable.

293   DTS temperature data for the three heated sections were isolated and analysed. The temperature

294   resolution for the XT-DTS at the temporal (10 s) and spatial (0.25 m) sampling applied in this study,

295   over 5km range, is estimated by the manufacturer to vary with a parabolic profile between 0.35 °C

296   (at 0m and 5,000m) and 0.20 °C (at 2,500m). In the buried sections analysed, the estimated

297   temperature resolution was ≤ 0.25 °C. Averaging the mirrored measurements at each depth allowed

298   for a further $1/\sqrt{2}$ improvement, leading to a temperature resolution of ≤ 0.18 °C in the buried

299   sections. As the three DTS instrument offer similar performance, this value is also representative for

300   the Ultima-M DTS and Ultima-S DTS.

301   Distributed thermal conductivity profiles were calculated for the four A-DTS tests by applying the

302   pre-asymptotic approximation method (Ciocca et al., 2012) to the heating phase of each heated DTS

303 spatial sample according to Equation 2, and performing a robust non-linear fit in Matlab to estimate

304 λ and t_0 simultaneously. The temperatures at t=0 to calculate the ΔT (K) during the heating were

305 taken as the average of 120 s of measurements prior to the heating, to reduce any noise in the

306 individual temperature measurement. The threshold time found varied between 60s (wetter soil

307 conditions) and 100s (drier soil conditions) after the beginning of the heating. At such short times,

308 the asymptotic stage was still not reached, and Equation 1 was not yet applicable, hence time

309 corrections were applied (as detailed in the methodology section). All time corrections t_0 were

310 negative and ranged between -55s and -100s, with threshold times longer than those found by

311 Ciocca et al., 2012 for the cooling phase. This is attributed to the longer times required during the

312 heating to approach the asymptotic regime.

313

314 Needle probe survey

315 A needle probe survey was conducted on 8th December 2016 to derive thermal conductivities for

316 the site as a means of validating the A-DTS-based method. It had been planned to supplement the

317 needle probe survey with an A-DTS campaign on the following day. However, this was not possible

318 due to problems with the power supply. Therefore, data from a previous A-DTS monitoring

319 campaign (completed on 25 October 2016) had to be used for the comparison, although it is

320 recognised that differing meteorological conditions and soil moistures may mean that the results are

321 not perfectly comparable.

322 _Instruments_: The survey was conducted using FTN01 and FTN02 Hukseflux Thermal Sensor systems

323 with single heated needles TP01 (length: 170mm, outer diameter: 6.35 mm) and TP04 (length: 150

324 mm, outer diameter: 3mm). The needles have a thermal conductivity measurement range of 0.1 to 6

325 W m-1 K-1 and radial footprint of ~100-300 mm (Hukseflux 2017). A KD2Pro Thermal Properties

326 Analyzer system (Decagon Devices 2016) was employed for obtaining more detailed measurements

327 at the depths of FO cable installation at a few sites. The KD2Pro system comes with two sensors, a

328   single-needle (TR-1) and a dual-needle (SH-1) sensor, and both were employed during the survey.

329   Since TR-1 is optimised for measuring thermal conductivity (while SH-1 is optimised for measuring

330   thermal dispersivity), only data from the single needle sensor TR-1 measurements are considered in

331   this paper. The TR-1 sensor has a length of 100 mm and a diameter of 2.4 mm. It measures thermal

332   conductivity in the range of 0.1 to 4.0 W m-1 K-1 with an accuracy of ±10-20% and within a radius of

333   ~30 mm around the probe (Decagon Devices 2016).

334   *Measurement campaign set up:* Measurements of thermal conductivity were conducted at 19

335   locations shown in Figure 1a along the instrumented slope and the surrounding area using the

336   Hukseflux probes. This involved coring a small (~5cm diameter) auger hole into the soil (using a

337   handheld auger) to a depth of 20cm/ 100cm into which the field needle probe was inserted vertically

338   (Figure 5a). Measurement interval of ~20-30cm and ~100-110cm were selected to (1) coincide with

339   the depth of the FO cable installation (at the instrumented slope) (green crosses, Figure 1a) and (2)

340   to be comparable to standardised measurement depths (the base of 100cm auger holes) for BGS

341   thermal conductivity assessments (unpublished data set) for a wider comparison. Measurements

342   were taken at the lower rate of power input (2.34 W m^{-1}), applying an equilibration period of 5 min

343   in all cases followed by a heating phase of 5 min (300 s).

344   A more detailed set of thermal conductivity measurements was taken at four, adjacent sites along

345   the instrumented slope (red triangles, Figure 1a) to test for variations in thermal conductivity

346   between the depths of fibre optic cable installation. Using the KD2Pro Thermal Properties Analyzer

347   system (Decagon Devices 2016), measurements were taken in dug holes at 10cm, 25cm and 40cm

348   depth (matching the depths of cable installation) by inserting the TR-1 Single Needle Sensor

349   horizontally into each measurement horizon (Figure 8b). A monitoring time of 300 seconds was

350   applied for the TR-1, during half of which the sensor was heated while the instrument collected

351   temperature measurements (over full length of read time). A 30-second equilibration period

352   preceded all measurements.

353

Results

Thermal conductivity measurements by A-DTS

The A-DTS thermal conductivity observations are shown in Figure 7 and summarised in Table 2 for

the different measurement campaigns and cable depths. The plots show that thermal conductivities

vary spatially, with depth as well as with distance along the cable. Localised sharp variations are

evident at a few meters spatial scale, demonstrating the high spatial resolution achievable by the A-

DTS method. Highest thermal conductivities were measured at 10cm depth, ranging between 1.01-

2.20 W m^{-1} K^{-1} with geometric means between 1.23 – 1.57 W m^{-1} K^{-1} for the different measurement

campaigns. Thermal conductivity ranges were similar at 25cm (0.70-1.88 W m^{-1} K^{-1}) and 40 cm depth

(0.78-2.01 W m^{-1} K^{-1}), but geometric means were somewhat higher at 40cm (1.08-1.36 W m^{-1} K^{-1})

compared to 25cm depth (1.01 – 1.27 W m^{-1} K^{-1}). This is mainly due to a drop in thermal

conductivity around 280-300 m along the cable, i.e. along the middle to upper reaches of slope 2.

The data show clear temporal variations in thermal conductivities related to seasonal precipitation

and associated soils moisture changes, with changes in geometric means between different

campaigns of up to 0.34 W m^{-1} K^{-1}, 0.26 W m^{-1} K^{-1} and 0.28 W m^{-1} K^{-1} at 10cm, 25cm and 40cm depth,

respectively. Even the campaigns undertaken on consecutive days (08th + 09th June 2016) show

considerable variations in thermal conductivity, e.g. changes of up to 0.17 and 0.12 W m^{-1} K^{-1} in

maximum and mean (geometric) values are observed at 40cm depth (Figure 7c). Since soil

compaction and mineralogy can be assumed to remain unchanged over the observation period,

these variations are attributed to changes in soil moisture content. However, the exact relationship

between soil moisture and thermal conductivity for soils at the study site is not known. Cosenza et

al. 2003 suggest an increase in thermal conductivity of 0.1 W m^{-1} K^{-1} for each 0.1 m^3 m^{-3} increase in

soil moisture. Assuming a similar relationship at the soils of the study site, some of the observed

pattern (e.g. thermal conductivities rise of 0.5 W m^{-1} K^{-1} between July and October 2016 at 10cm

378   depth – Figure 7a) cannot be explained by soil moisture changes alone (Figure 4a), and must be due

379   to some experimental error (as discussed further below).

380

381   Thermal conductivity measurements by needle probe sensors

382   Thermal conductivity values measured with the Hukseflux needle probes are shown in Figure 9 and

383   summarized in Table 3 and Figure 10. Values range between 0.83 and 2.63 W m^{-1} K^{-1} (geometric

384   mean 1.82 W m^{-1} K^{-1} for n=24). The data show no observable spatial trend. A bulk thermal

385   conductivity for the site of 1.82 W m^{-1} K^{-1} (geometric mean) is estimated from the (Hukseflux)

386   measurements points (Figure 9). The running arithmetic mean, median and geometric and the 95%

387   confidence interval are plotted (Figure 11) to assess representativeness of the result for the site, as

388   suggested by King et al., (2012). Figure 11 illustrates that 11 and 22 measurements are required to

389   determine bulk thermal conductivity for this site with standard errors of <±15% and <±10%,

390   respectively.

391

392   Thermal conductivities measured with the KD2Pro sensor are slightly higher than those obtained

393   using the Hukseflux probes (by approximately 10%), while their standard deviation is smaller. Figure

394   10a suggests similar median of thermal conductivities at 10cm and 25cm, but a somewhat higher

395   median value at 40cm depth (as measured by the KD2Pro probe). However, observations for the

396   individual horizons are so few (n=4) that it is not possible to draw statistically meaningful

397   conclusions. Thermal conductivities at 25cm and 100cm depths (measured by the Hukseflux probes)

398   also show a small difference in median values, but the overlap in range suggests that the data points

399   belong to the same data population and hence, have the same bulk thermal conductivity.

400

401   Comparison of DTS versus needle probe thermal conductivities

402   Thermal needle probe data are used in this study as a way of assessing the ability of A-DTS to obtain

403   thermal conductivity in a heterogeneous field setting. Direct comparison of the A-DTS data with data

404   from the needle probe survey are complicated by the fact that the A-DTS campaign and needle

405   probe surveys were not conducted at the same dates, i.e. on 25/10/2016 and 08/12/2016,

406   respectively. Nevertheless, some general observations can be made in comparing the data sets:

407   both data sets, the A-DTS and Hukseflux data show a large degree of variability in thermal

408   conductivities, e.g. due to inhomogeneities in soil composition and porosity, thermal conductivity of

409   the solid fraction and variability of moisture content (Cosenza et al. 2003; King et al. 2012) which can

410   be expected in a heterogeneous deposit such as Boulder clay/ Diamicton (Figure 2). While A-DTS

411   data show a similar degree of dispersion (spread) compared to the needle probe data (Figure 11),

412   the data sets show a statistically significant difference in means ($p<0.001$), with central values for the

413   A-DTS-derived thermal conductivities being about 25% lower than those obtained by the needle

414   probes. A number of causes may have contributed to the observed differences in measured thermal

415   conductivity ranges between the two methods, as discussed below:

416   Soil Conditions

417   1. Soil moisture changes may have contributed to the discrepancy between the A-DTS

418   measurements, obtained during a period of lower rainfall and soil water contents (Figure 4), and

419   the needle probe measurements, which coincided with a wetter period and higher soil water

420   contents (Figure 4). However, the overall effect of the soil moisture increase (0.01 $m^3 m^{-3}$ - 0.09

421       $m^3 m^{-3}$, median 0,04 $m^3 m^{-3}$, as measured by the FDR probes) on thermal conductivity is likely to

422   be small, i.e. < 0.1 W $m^{-1} K^{-1}$, assuming an increase in thermal conductivity of 0.1 W $m^{-1} K^{-1}$ for

423   each 0.1 $m^3 m^{-3}$ increase in soil moisture (Cosenza et al. 2003).

424   2. The effect of soil compaction must also be considered as it increases the bulk density and

425   decreases the porosity of a soil, and thus can impact on soil thermal conductivity. For example,

426   increases in bulk density of 0.16 g cm^{-3} (11%) in clay loam and 0.18 g cm^{-3} (12%) in sandy loam

427   were found (in a laboratory setting) to result in significant increases in the soil thermal

428   conductivity of up to 0.27 (44%) and 0.83 W m^{-1} K^{-1} (73%), respectively (Abu-Hamdeh 2001). The

429   FO cables were installed in an excavated trench that was backfilled with disturbed soil and then

430   re-compacted (as explained previously). Needle probe measurements were taken adjacent to

431   these refilled trenches and across the wider site. The difference in soil compaction between the

432   refilled and non-disturbed soils may have contributed to the lower thermal conductivity values

433   obtained by the A-DTS during the earlier campaigns (October 2015). However, overall (and

434   specifically during the later campaigns when soils had further compacted) the difference is

435   thought to be relatively minor as, firstly, soil compaction had been applied around and above

436   each cable during installation and, secondly, tree planting activities in 2014, one year prior to the

437   cable installation, are likely to have changed soil bulk density distributions across the site.

438

439   Fibre optic cable properties and geometry

440   3. The larger diameter of the fibre optic cable compared to the needle sensor, and the higher

441   thermal resistance due to the presence of an insulation jacket in the cable, instead of bare

442   metal, lead to longer times required for reaching the asymptotic stage (i.e. linearity in

443   temperature increase as a function of natural logarithm of time). According to Ciocca et al.,

444   (2012), the heating is slower than the cooling phase to reach the log-linear regime. Witte et al.,

445   (2002) gives a heating time of $t \geq 5\,r^2/\alpha$, where r is the cable radius in meters and α the

446   thermal diffusivity of the jacket in m^2 s^{-1}, for log-linear conditions to be reached. Assuming a

447   thermal diffusivity of PVC ($\alpha=8e^{-8}\ m^2\,s^{-2}$) and a radius $r=0.0035m$, linearity is attained after 750s.

448   Therefore, the solution in Equation 2 may not be sufficient to compensate for the use of data

449   from the pre-asymptotic (transient) stage in the processing, leading to an underestimation of the

450   computed thermal conductivities.

451   4.   Figure 5 shows the arrangements of components within the DTS cable. From that, it is obvious

452   that the assumption of a cylindrical source within the soil is not strictly met when using the DTS

453   cable. Hence, the underlying assumption of the probe method are not fully adhered to, and this

454   may impact on the derived solution. In another study, the influence of the thermal conductivity

455   of the outer sheath material (which was lower than that of the surrounding medium) was

456   suggested to have contributed to the underestimation of thermal conductivities measurements

457   by the DTS (Sakaki et al. 2019).

458   Power supply limitations

459   5.   The petrol generator only allowed for a maximum power rate of 5W/m. Although other A-DTS

460   investigations used similar power inputs for soil moisture measurements (Striegl and Loheide,

461   2012), it may be too low for the specific cable design adopted in this study. The positive

462   correlation between power input and the accuracy of A-DTS-derived measurements has been

463   demonstrated by Dong et al (2017) for soil moisture measurements. Furthermore, the power

464   output from a petrol generator is unavoidably less constant/ stable compared to a mains power

465   source, and fluctuations in the applied power rate during the heating phase are likely to have

466   added to the experimental uncertainty; e.g. it is believed to be the main reason for the observed

467   variability during consecutives survey as in June 2016 (Figure 7c). The system has since been

468   connected to mains power, and is currently being retested.

469   Instrument characteristics

470   6.   The observed differences in thermal conductivity values produced by the different methods may

471   be attributable to the difference in soil volumes over which measurements are integrated.

472   Assuming a radial footprint of 100-300mm for the Hukseflux, the measured volume for the

473   needle probes is between 4 – 40 L. There are no data yet available on the volume of soil

474   influenced by the heating of the fibre optic cable, but the radial footprint of FO cable is

475   estimated to be < 30 mm around the cable (Weiss, 2003). At distances greater than that the

476   temperature increase becomes smaller than the instrument temperature resolution. The

477   measured volume of soil per DTS spatial sample (0.25m) is therefore ≤ 1 L. The heating time

478   required to expand the footprint to be comparable with the needle probes would introduce axial

479   diffusion effects, making the A-DTS technique not applicable. The limited footprint allows for a

480   fine horizontal characterization of the soil, identifying variability into centimetres-thick layers.

481   Differences in measured soil volume may also be responsible for the variability in measured

482   thermal conductivities between the Hukseflux and the KD2Pro sensors of about +/-10 %.

483   However, the obtained precision is generally consistent with findings from an inter-laboratory

484   study, which indicated a measurement precision of between +/-10 and +/-15 % for different

485   needle probes, and identified a general tendency to a positive bias (higher value) over the

486   known values for the materials studied (ASTM 2000).

487   Uncertainty assessment and calibration:

488   7.   Temperature resolution of the measurements along the installed cable was tested and was

489   found to follow the parabolic curve typical for double ended configuration with lower resolution

490   of 0.35 ^{o}C at the cable ends (at 0m and 5,000m) and highest resolution of 0.20 ^{o}C along the mid-

491   section of the cable (at 2,500m). The averaging of the mirrored temperatures per each depth

492   allowed for a further improvement of a $1/\sqrt{2}$ factor in the buried section, with resolution ≤ 0.18

493   ^{o}C. Calibration for thermal conductivity (λ) was not undertaken for the A-DTS installation

494   presented in this study. However, calibration and detailed error analysis of the method has been

495   carried out in a previous study, and validity of the approach was proven in a setting of known

496   soil properties and thermal conductivity distribution as described in Ciocca et al., (2012).

497   Uncertainties in λ were found to be < 6% for their method, as used in this study but applied to

498   the cooling phase. However, cable geometry and heating strategies differ within each field

499   application, and the calibration coefficients vary along the cable depending on surrounding soil

500   properties and moisture conditions. An absolute calibration, as done for needle probes (e.g. by

501   means of measurements on substance of known thermal conductivity), is not possible for such

502   field application due to the scale and size of the installation and the fact that field settings are

503   largely variable and unknown. In conventional TRT tests, for example, observed water

504   temperature variations are fitted with a mathematical model (often the line-source model) to

505   estimate the thermal properties of the subsurface and the borehole that forms part of the

506   borehole heat exchanger installation. As there is no "reference" ground with known

507   characteristics, on-site calibration of the method and uncertainty assessment are usually not

508   possible. Recently, the concept of an aboveground virtual borehole has been suggested to

509   calibrate TRT units for different ground thermal conditions and conductivities (Corcoran et al.

510   2019), or factorial analysis has been carried out to assess the uncertainty associated with the

511   measurements (Raymond et al. 2011), but such assessments remain rare in the context of TRTs.

Discussion

512

513   A-DTS permits repeated interrogation of soil properties at the exact same locations using active or

514   passive measuring modes. It, therefore, has utility for detailed monitoring of changes in soil

515   properties, e.g. in response to external stresses, such as plant water uptake, climate change or

516   repeated heating/ cooling associated with ground source heat pump and heat storage operations.

517   For the determination of thermal conductivities for ground source heat pump applications, it is

518   generally recommended that measurements should be taken during dry periods to derive a

519   conservative estimate (King et al, 2012), but little consideration is given to the temporal variability of

520   thermal conductivities. Here we present some preliminary findings from four A-DTS campaigns. The

521   data suggest that thermal conductivities at the study slope vary by up to 30% between the

522   measurement campaigns, with variations of up to 10% occurring between consecutive days.

523   However, these findings are based on 4 measuring campaigns only, subject to the inherent

524   experimental uncertainty discussed above. Some of these uncertainties have now been addressed,

525   e.g. by replacing the generator with a mains power source. Furthermore, longer-term A-DTS

526   monitoring with sequential (mains powered) heating of 900 s per depth has since been undertaken

527   at 6 hours intervals, to further test repeatability of measurements and assess changes in soil thermal

528   conductivity and soil moisture with different approaches. These new data sets are currently being

529   analysed and will provide further insight into the temporal dynamics in thermal conductivity at the

530   daily and the seasonal scale. Such knowledge could inform operational strategies for ground source

531   heat application, specifically optimisation of system efficiencies.

532   By providing high spatial and temporal resolution data over long time and large spatial extents, A-

533   DTS methods have the potential to serve as an "across the scale" tool that can fill the gap between

534   point sensors (high-frequency measurements at small spatial footprints) and remote techniques

535   such as COSMOS and satellites observations (low-frequency measurements at large, averaged

536   footprints and shallow penetration depths). At this intermediate scale, spatial coverage and

537   resolution provided by the DTS method, i.e. 0.25m-spaced measurements over 1.5km of heated

538   cable, remains unprecedented.

539   Certainly, the monitoring objective must be such that installation times of several weeks and costs of

540   several tens of thousands GBP (for instrumentation and installation) can be justified. Measurements

541   of thermal conductivities, e.g. for the design of routine ground heat application, will not require an

542   A-DTS installation, except where detailed temperature/ thermal conductivity monitoring of the

543   installation during operation is of interest. In most of these standard cases, needle probe surveys

544   offer a much more cost and time-effective method, and it has been confirmed in this study that

545   representative estimates of bulk thermal conductivity can be obtained with comparatively little

546   effort, i.e. requiring 22 needle probe measurements to yield an estimate of the bulk thermal

547   conductivity representative of conditions at the study site (on the day measurements were taken)

548   and with errors <10%.

549   However, for applications requiring (1) long term monitoring, (2) at high temporal repeatability, (3)

550   over long distances and (4) with minimum soil disturbance, the A-DTS provides and extremely valuable

551 tool. Leak detection along pipelines, dams and infrastructures, or in-situ monitoring of soils to

552 optimise irrigation of agricultural crops, are examples where A-DTS may lead to critical benefits that

553 justify cost and installation effort.

554 Further work is needed to better understand the heat transfer processes within the innovative cable

555 geometries such as the one applied in this study, and to improve data analysis techniques. Modelling

556 of the heat transfer within a complex structure as the heated FO cable by means of advanced

557 software (e.g. Comsol Multiphysics) should be performed in order to provide critical insights on the

558 actual temperature increase of the soil compared to the core of the cable, the radial footprint, the

559 timescales involved and the optimal power rate required, improving the applicability of the A-DTS

560 technique. The high density of measurements may supply local temperature, thermal conductivity

561 and soil moisture data, which can then be converted into information relating to heat and water

562 fluxes in the subsurface. Such data can be used to drive and/or validate eco-hydrological models,

563 contributing to critically-needed improvements in smart-irrigations techniques; ground source heat

564 pump optimisation and heat storage system designs, as well improving leak detection from sensitive

565 infrastructures such as sewers and water pipes, or oil and gas pipelines.

566 Further testing and validation of the method is required, including simultaneous A-DTS and Needle

567 Probe campaigns as well as an assessment of the impact of different heating strategies on the

568 surrounding soil. This will permit the optimisation of the method, balancing power input against

569 accuracy of thermal conductivity estimations, as well as provide an assessment of the measurement

570 footprint of the method.

571 ## Conclusions

572 This study has demonstrated that active DTS has the potential to provide a promising alternative for

573 measuring thermal conductivity at the field scale at high spatial and temporal resolutions. Active DTS

574 produced results within the range of thermal needle probe measurements in terms of spread of the

575   values, although with statistically significant lower central values. Further testing and improvements

576   are required that address the experimental uncertainties inherent in the methodology and set up

577   applied in this study.

578   While initial installation of the A-DTS system is more time consuming and expensive than a needle

579   probe survey (but similar in cost to a standard TRT), it has some key advantages: (1) the methods can

580   provide distributed measurement for horizontal BHE systems (as opposed to TRTs which are

581   currently only available for vertical BHE systems), (2) it provides spatially-distributed thermal

582   conductivities instead of a single bulk value, and (3) measurements are easily repeatable. The latter

583   can be of particular advantage where the temporal variability in thermal properties due to changing

584   soil moisture conditions or the influence of groundwater flow on heat transport and thermal

585   properties needs to be assessed.

586   A number of factors have been identified that may have affected the thermal conductivity

587   estimations at the A-DTS. The impact of these factors on the overall measurement precision has not

588   been investigated in detail, and further studies are necessary to better understand these effects and

589   to optimise method operational parameters and analysis.

590

Acknowledgement

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739

740

Tables

742   Table 1: Details of the A-DTS tests performed between October 2015 and October 2016

Survey date [dd/mm/yy]	Power Density Q [W m^{-1}]	DTS sampling [m]	DTS time interval [s]	DTS model
23/10/15	3.3±1%	0.25	20	XT-DTS
08/06/16	3.7±1%	0.25	10	Ultima-M
09/06/16	4.8±1%	0.25	10	Ultima-M
25/10/16	5.0±1%	0.125*	10	Ultima-S

743

744   Table 2: Statistical analysis of thermal conductivities λ (W m^{-1} K^{-1}) from A-DTS at the different cable

745   depths. *Data were spatially interpolated for the analysis to get the same spatial sampling of 0.25m

	23/10/2015	08/06/2016	09/06/2016	25/10/2016	Maximum difference in λ between campaigns
10cm depth					
n	1928	1928	1928	1928	
Minimum	1.02	1.01	1.02	1.29	0.28
Median	**1.29**	**1.21**	**1.25**	**1.56**	**0.35**
Maximum	1.66	1.70	1.80	2.20	0.50
Arithmetic mean	1.30	1.23	1.27	1.58	0.35
Standard deviation	0.11	0.11	0.12	0.14	0.03
Geometric mean	**1.29**	**1.23**	**1.26**	**1.57**	**0.34**
25cm depth					
n	1928	1928	1928	1928	
Minimum	0.70	0.70	0.70	0.78	0.08
Median	**1.13**	**1.01**	**1.02**	**1.29**	**0.28**
Maximum	1.62	1.53	1.56	1.88	0.35
Arithmetic mean	1.11	1.02	1.03	1.28	0.26

Standard deviation	0.15	0.16	0.16	0.17	0.02
Geometric mean	**1.10**	**1.01**	**1.02**	**1.27**	**0.26**
40cm depth					
n	1928	1928	1928	1928	
Minimum	0.93	0.78	0.85	1.00	0.21
Median	**1.25**	**1.09**	**1.20**	**1.35**	**0.26**
Maximum	1.83	1.64	1.81	2.01	0.37
Arithmetic mean	1.26	1.09	1.21	1.37	0.28
Standard deviation	0.14	0.13	0.16	0.14	0.03
Geometric mean	**1.25**	**1.08**	**1.20**	**1.36**	**0.28**

746

747 Table 3: Summary of thermal conductivities λ (W m-1 K-1) from (a) Huxefluks and (b) KD2Pro needle

748 probes and (c) A-DTS campaign on 25/10/2016

	(a) Hukseflux (all data)	(b) KD2Pro (all data)	(c) A-DTS 25/10/2016 (all data)
n	24	12	5784
Minimum	0.83	1.76	0.78
Median	**1.88**	**2.02**	**1.39**
Maximum	2.63	2.82	2.02
Arithmetic mean	1.87	2.09	1.41
Standard deviation	0.45	0.27	0.20
Geometric mean	**1.82**	**2.07**	**NA**

749

750

774   and 100cm depth.) and (b) KD2Pro Thermal Properties Analyzer with TR-1 Single Needle Sensor

775   (inset) (Needle horizontally inserted for measurements of 10cm, 25cm and 40cm soil horizon). The

776   dual-needle probe of the KD2 was not used for this study.

777   Figure 9: Distribution of thermal conductivities measured by Hukseflux FTN01/02 thermal needle

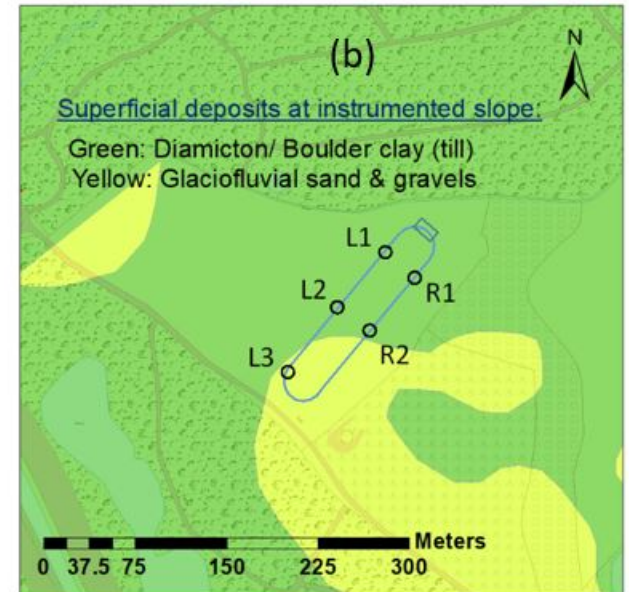778   system at depths of cm.

779   Figure 10: Whisker plot of thermal conductivities measured by (a) needles probes and (b) A-DTS on

780   25/10/2016 at different depth horizons

781   Figure 11: Plot of arithmetic mean, median, geometric mean and 95% limits of confidence against

782   number of measurements for successive needle probe (Hukseflux) determinations.

(a)

Stream

BIFoR FACE field site

13
12
14
11
23
10
15
16
17
22
FO cable
21
3
20
5
2
6

1
8
7

Heat pulse and
A-DTS system

Soil moisture probes
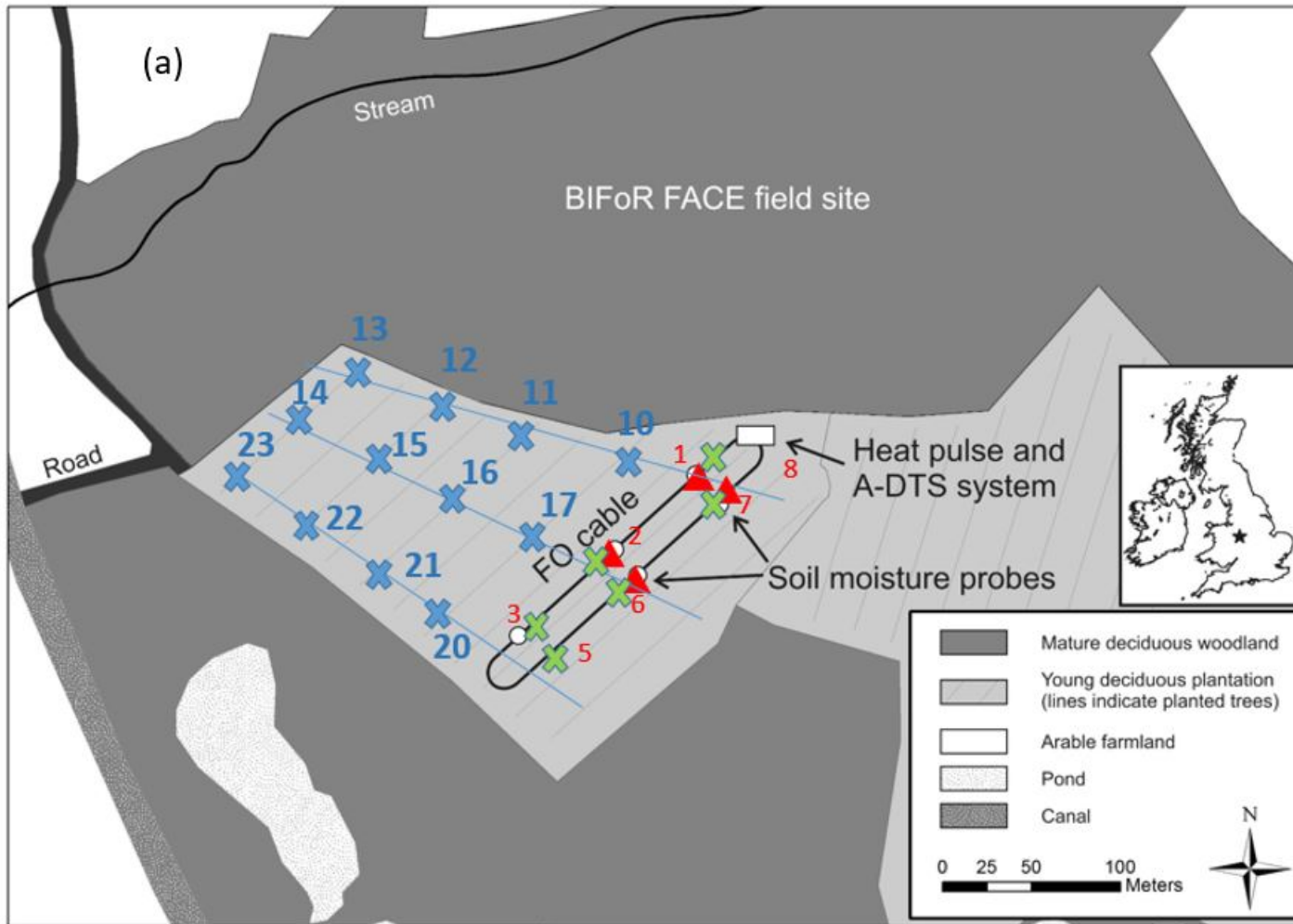
Auger hole measurements
(Hukseflux) & soil sampling
Depths: **100cm**, (30cm)

Measurements on dug profile
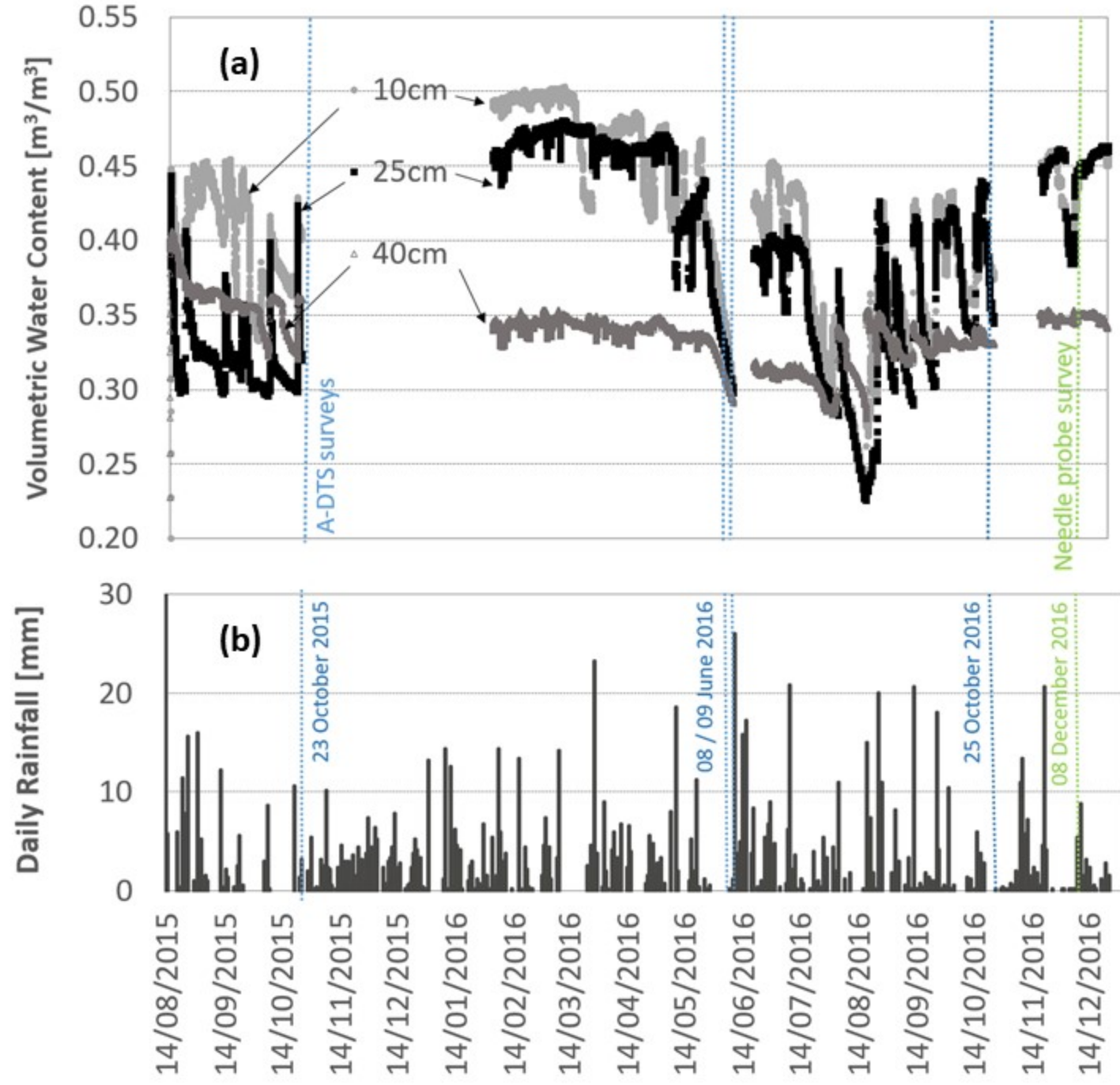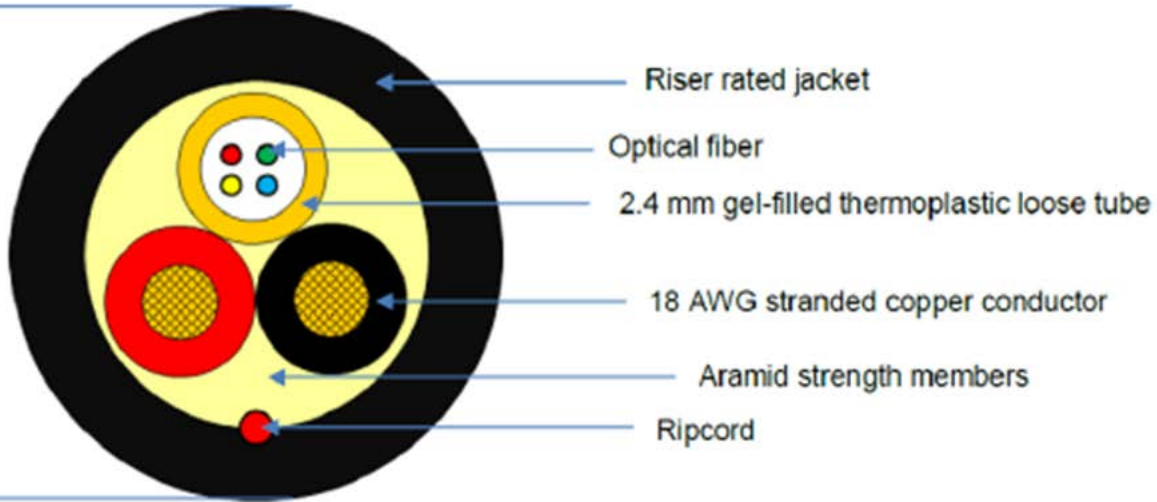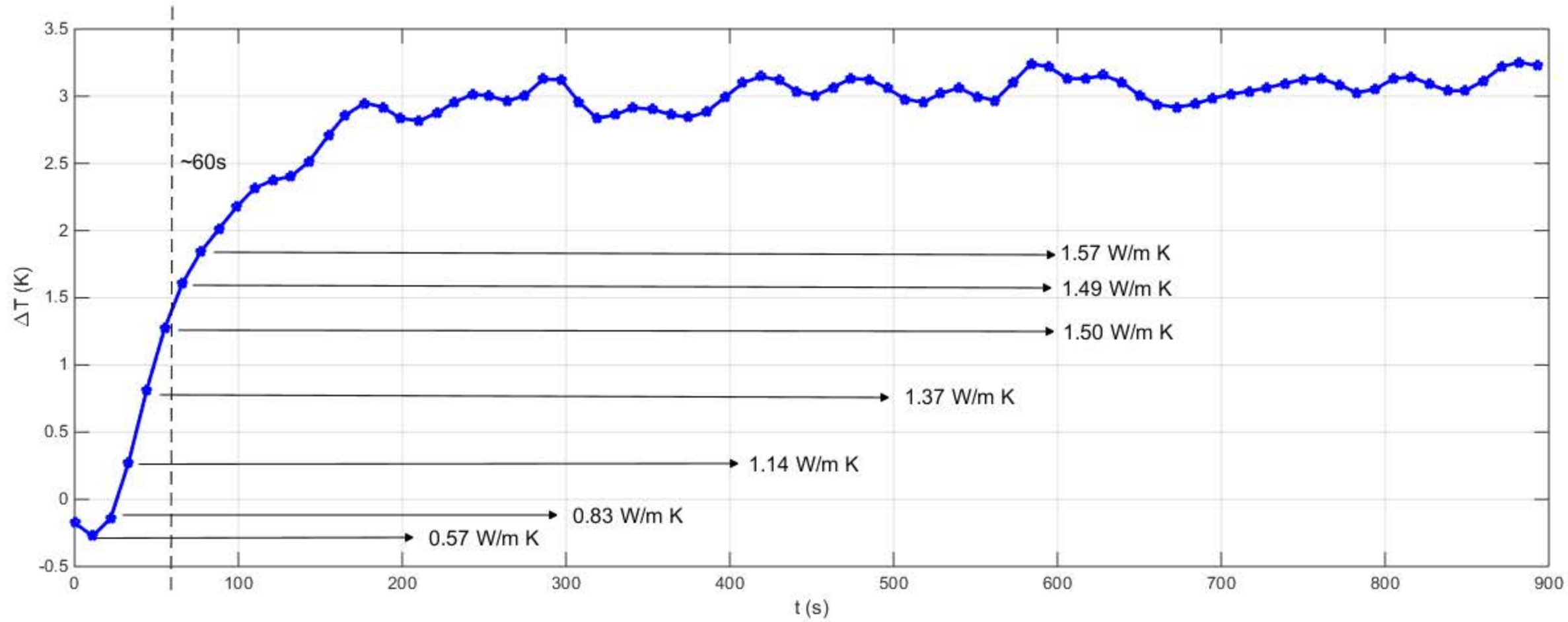(KD2Pro probes) & soil sampling
Depths: **10cm, 25cm, 40cm**

Road

Mature deciduous woodland

Young deciduous plantation
(lines indicate planted trees)

Arable farmland

Pond

Canal

0 25 50   100
Meters

N

(b)

N

Superficial deposits at instrumented slope:

Green: Diamicton/ Boulder clay (till)
Yellow: Glaciofluvial sand & gravels

L1
L2
R1
L3
R2

Meters
0 37.5 75   150   225   300

(a)

(b)

Figure (a) Volumetric Water Content [m³/m³] and (b) Daily Rainfall [mm] time series from 14/08/2015 to 14/12/2016, showing measurements at 10cm, 25cm, and 40cm depths with A-DTS surveys and Needle probe survey markers.

Riser rated jacket

Optical fiber

2.4 mm gel-filled thermoplastic loose tube

18 AWG stranded copper conductor

Aramid strength members

Ripcord

7.7 mm

(a)

(b)

(c)

(a)

(b)

(a) Thermal needle probe survey [08/12/2016]

(b) A-DTS survey [25/10/2016]

Thermal conductivity (W/mK)

■ 10cm (KD2Pro) [n=4]
■ 25cm (KD2Pro) [n=4]
■ 40cm (KD2Pro) [n=4]
■ 25cm (Hukseflux TP04) [n=6]
■ 100cm (Hukseflux TP01 and TP04) [n=18]
■ 10cm (DTS) [n=1928]
■ 25cm (DTS) [n=1928]
■ 40cm (DTS) [n=1928]

Survey date	Power Density Q	DTS sampling	DTS time interval	DTS model
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