DTS ground temperature measurements in mountain permafrost – the 2Alpes-3065 borehole (French Alps)

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ABSTRACT
A 100 m deep borehole in mountain permafrost has been equipped with both a thermistor chain and a fiber optic cable for Distributed Temperature Sensing. The device permits to assess the resolution and accuracy of DTS measurements through the comparison of parallel DTS profiles and with classical sensors. First results show that a resolution in the order of 0.1 °C can be achieved, but that the accuracy is strongly dependent on the calibration of the measurement.

RÉSUMÉ
Un forage de 100 m de profondeur dans le permafrost de montagne a été équipé à la fois d'une chaîne de thermistor et d'une fibre optique pour la mesure DTS. L'installation permet d'evaluer la résolution et la précision des mesures DTS, par la comparaison de profils DTS parallèles avec les mesures de capteurs classiques. Les premiers résultats montrent que la résolution est de l'ordre de 0.1 °C, mais que la précision dépend fortement de la calibration de la mesure.

1 INTRODUCTION

Fiber Optic Distributed Temperature Sensing (FO-DTS) appears to be an appropriate technology to address the specific challenges of precise temperature measurements in permafrost and has been installed for the present experiment. The measurement principle is based on the scattering of a laser light pulse in the optical fiber. The analysis of the spectrum of the returned light allows a temperature calculation. Light travel time is used to determine the distance from the light source to a given point on the fiber. This technique permits a spatial resolution of 1 m (most recent instruments even up to 25 cm) and a relative temperature resolution inferior to 0.1°C, depending on the instrument used, on the sampling frequency (which may be a function of the thermal stability or inertia of the considered system), and on the measurement distance. The sampling frequencies can range from a few seconds up to several hours and fibers of up to several kilometers can be measured.

DTS has been used for several years in environmental sciences. It has been used in hydrologic studies (e.g. Selker et al., 2006a,b; Westhoff et al., 2007; 2011; Roth et al., 2010; Vogt et al., 2010), in cryospheric science (Selker et al., 2006a; Tyler et al., 2008; Tyler et al., 2013), limnology (Vercauteren et al., 2011), boundary layer meteorology (Keller et al., 2011; Thomas et al., 2012), or in soil science (Steele-Dunne et al., 2010; Ciocca et al., 2012). Several previous studies have used DTS for ground temperature measurements, particularly in relation with soil moisture or ground water flow (e.g. Lowry et al., 2007; Sayde et al., 2010; Lauer et al., 2013) As far as we know, there has been only one published study adressing subsurface permafrost temperatures in a borehole (Freifeld et al., 2008) for the determination of substrate thermal conductivity at a meter resolution. Apart from this study DTS has been used by Roger et al. (this volume) for freeze/thawing surface monitoring along a linear infrastructure in permafrost. The present paper focussses on seasonal observation of a full annual cycle of permafrost borehole temperatures at a high Alpine site.

The paper presents the first monitoring results from a 100 m deep borehole in the French Alps, which is equipped to simultaneously measure temperature with classical thermistor sensors and using the DTS technique (Schoeneich et al., 2012). It evaluates the use of DTS for this type of measurements, with particular focus on methodological issues related to the DTS technique.

Figure 1. Location of the borehole 2Alpes-3065.

2 STUDY SITE AND METHODS

2.1 The borehole 2Alpes-3065

A 100 m deep borehole was drilled in September 2010 through permafrost ground in the upper part of the ski resort of Les Deux Alpes, in the French Alps (Massif des Ecrins, 45°00'00'' N / 6°11'30'' E, 3065 m a.s.l., Figure 1). The borehole has been equipped for ground temperature measurement and is a key site of the French observation network PermaFRANCE, of the international Alpine permafrost monitoring network PermaNET, and of the GTN-P global monitoring network of permafrost.

The borehole was drilled in September 2010 by dry percussion drilling, with compressed air. It has a diameter of 120 mm, and has been cased with an 83 mm PVC tube down to a 98 m depth. All joints were made waterproof with silicone, and the tube was sealed at its bottom by a watertight plug, according to standard procedures. A concrete case was installed around the borehole head where the instrumentation has been placed.

The borehole is entirely in homogenous paragneiss bedrock, covered by ca 2 m of in situ frost shattered rock.

2.2 Borehole equipment

The borehole was equipped in December 2010, according to GTN-P standards, with a thermistor chain, consisting of 30 PT100 temperature sensors at depths corresponding to the GTN-P guidelines.

In addition to the thermistor chain, the borehole was equipped with an optical fiber cable, in order to simultaneously measure temperature using the DTS technique (Figure 2). A 700 m long fiber optic cable was installed in the borehole in two loops (Figure 2). The first loop was taped on the outside of the plastic tube and pushed down the borehole with the tube. The second loop was placed inside the plastic tube, together with the thermistor chain. This setup has permitted to measure both the temperatures in direct contact with the ground and those inside the open tube, in order to detect any possible influence of air convection within the tube.

A 50/125 µm quartz graded index multimode fiber optic cable with a 2.8 mm outer diameter plastic coating has been used. The fiber optic cable has been customized with an E2000 connector at each end including the necessary 8° angle cut to avoid reflection and loss. The 700 m long cable was used as follows (Figure 2): the first 100 m were left outside for calibration, the next 200 m were used for the outer loop in the borehole; an intermediate section of 100 m was left outside the borehole for calibration purposes, and another 200 m section was used for the inner loop, while the last 100 m section was left outside again for the cable calibration. This setting provides four parallel temperature profiles for each measurement run.

2.3 DTS measurement protocol

DTS measurements were made using an APSensing (Agilent) N4386A instrument built in 2007. This instrument has a spatial resolution of 1 m and a temperature

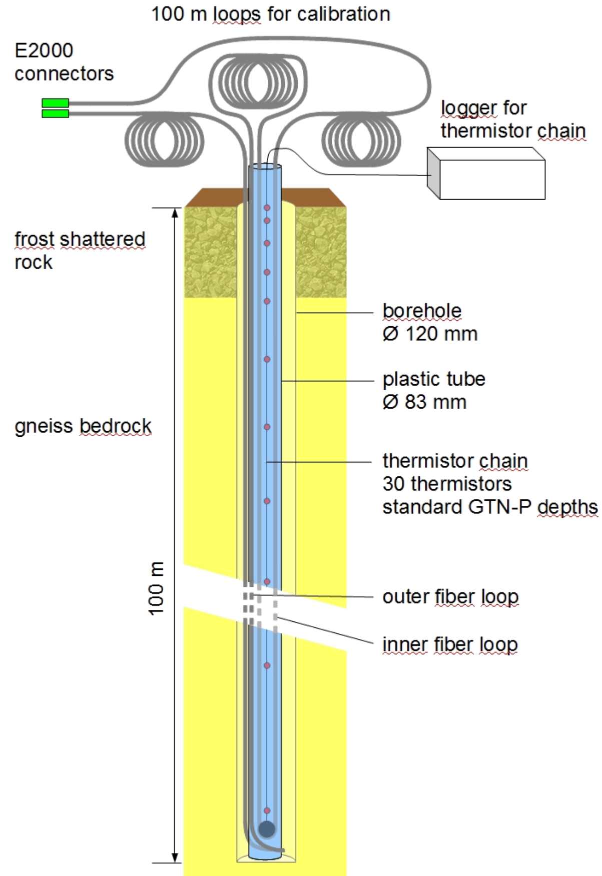

Figure 2. The borehole equipment.

resolution of 0.1°C. Despite the fact that in the meantime more efficient instruments with better spatial resolution and accuracy have been available, it was chosen because of its suitability for outdoor use in harsh environments and possible operation at low temperatures.

Since the instrument could not be run continuously on the site, short duration, periodic measurements were performed. The first measurements were made in February 2011 in very cold winter conditions (-15°C and 20 m/s wind). Only single ended measurements could be performed because of a defective connector. Measurement time was limited because the ice-bath was freezing. The fiber was measured for 30 minutes.

No measurement could be made in 2012, because of an instrument failure and its subsequent revision. A second set of measurements was performed in 2013 with the goal of sampling an annual cycle at 3-month intervals. These measurements were performed on January 30, April 16, July 17 and December 4, so to get typical seasonal profiles. Several different measurement protocols were tested to determine the most suitable configuration. The standard protocol retained for the four dates was a measurement time of one hour in each direction. The measurement duration was limited by the power supply from the battery and, in winter, because of the freezing of the calibration bath.

For calibration, the three calibration cable sections were submerged in a slush bath prepared with water and snow available on the site. The temperature of the slush bath was monitored with a PT100 sensor mounted on a carbon avalanche probe. In January and April, the bath was prepared in a simple plastic bin. Since in April it was difficult to keep the bath temperature at 0°C, the bin was afterwards replaced by an insulated camping cooler box.

One difficulty of the DTS method was to determine the exact positioning and, in this case, to correlate the four parallel downhole and uphole profiles. In order to overcome the problem, a short section (30 cm) of the four parallel fiber cables were wrapped in July 2013 in a dark plastic bag, one meter above borehole top, and exposed to sun. This induced a clear warm peak on the temperature profiles, which was used to correlate the four profiles.

2.4 Data processing

The raw data consist in a continuous 1 m resolution record of relative temperature (temperature trace), and of signal intensity loss (dB) with the corresponding distances from the light source. These data were first calibrated by removing the initial temperature offset, and then the slope, by using the three calibration sections. When measured in both directions, the calibration values could be averaged between the two directions. In a second step, the calibration sections could be removed, the record divided into the individual downward and upward sections, and the upward sections direction inverted. The four sections were then matched, using the warm peak from a black plastic wrap as a reference marker.

The absolute difference between parallel downhole and uphole profiles, for the outer and the inner loops, were calculated, in order to assess the accuracy of the measurement. Parallel profiles were averaged and standard deviation calculated.

3 RESULTS

3.1 Permafrost temperature

With a temperature of -1.3°C at the Zero Annual Amplitude (ZAA) depth of 35 m, the 2Alpes-3065 borehole shows values comparable to other boreholes at similar altitude in the Alps. The bottom temperature of -0.7°C indicates that the permafrost thickness is more than 100 m.

3.2 Accuracy of DTS measurements

According to the manufacturer's specifications, and given the integration period of 1 hour assuming steady state conditions of the investigated system, the DTS unit in use is rated to reach a measurement accuracy of better than 0.1°C. The temperature in the permafrost borehole can be considered as absolutely stable over the 1-hour time interval of the measurement. Thus the installation of the 2Alpes-3065 borehole offers the opportunity to compare four parallel profiles for every measurement run.

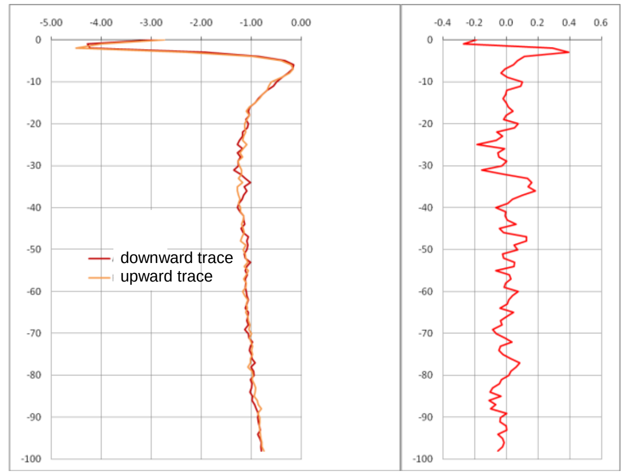

Figure 3. DTS measurements of January 2013. Left: downward and upward temperature profiles. Right: difference between the two profiles.

Figure 3 shows the downward and upward temperature profiles of the outer loop for the January 2013 measurement run. It appears that most measurements are within ±0.1°C, but that differences of up to 0.2°C can be observed at the same depth on individual measurements, whereas the uppermost meters show larger deviations. The mean absolute differences and the standard deviation of the parallel measurements were calculated for the sections 5-98 m depth and the corresponding results are given in Table 1. The match is always better for the outer loop, which two sections are wrapped together, than for the freely suspended inner loop. The accuracy is better for the January and April measurements, in the order of 0.05°C, than for the July and December measurements, were differences reach or even exceed 0.1°C. The mean differences between the averaged outer and inner loops and the standard deviation of the four traces are in the same order. Since these differences are calculated on single measurement runs, they are independent from the offset calibration (see below) and thus represent a good evaluation of the measurement accuracy. Differences between the outer and inner loops could however be influenced by the signal loss correction.

Table 1: mean absolute differences between downward and upward sections of inner and outer loop, mean difference between outer and inner loops, and standard deviation of all four traces for the four measurement runs.

	Jan	April	July	Dec
mean difference loop 1	0.048	0.054	0.096	0.089
mean difference loop 2	0.063	0.093	0.129	0.100
difference loops 1-2	0.062	0.055	0.133	0.174
stand dev 4 traces	0.055	0.062	0.113	0.122

mean difference = mean of absolute differences 5-98 m

Figure 4 shows the averaged temperature profiles (mean of four traces) at the four measurement dates, and Table 2 gives the calculated mean relative differences between the four profiles, calculated on the 30-98 m depth sections, considered to be stable on a annual cycle (below ZAA depth). All four profiles appear to be very parallel and similar in shape, and thus show no sign of any profile disturbance by air convection or other seasonal effects. The mean differences range from 0.021°C to 0.246 °C. These values are strongly dependent on the offset calibration, which will be discussed further. They nevertheless indicate that the replicability of the measurement, and thus its ability to detect temperature changes between two measurement runs is in the range of ± 0.1°C, similar to that of classical thermistors

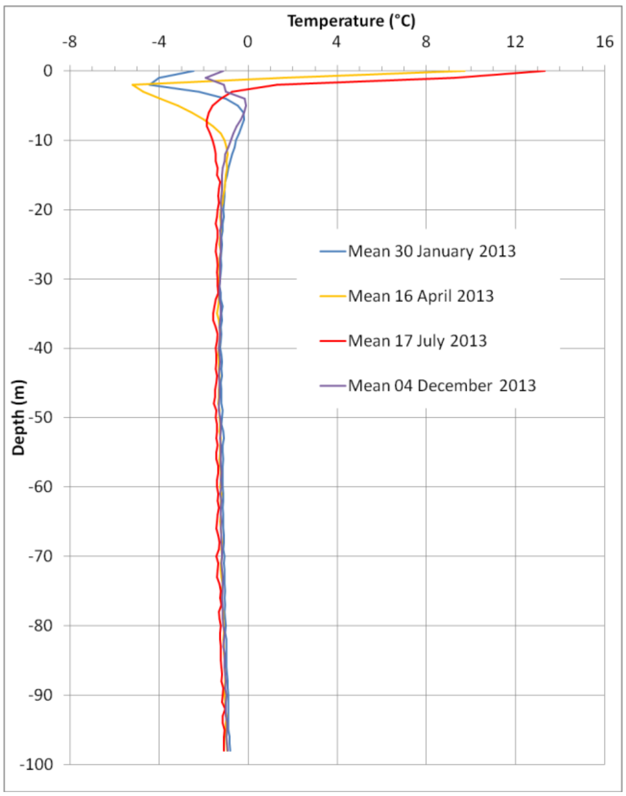

Figure 4. Averaged temperature profiles at the four measurement dates. Each profile is the mean of 4 single traces.

Table 2. Mean relative difference of averaged temperature profiles (mean of four traces) between the four measurement dates.

	April	July	December
January	0.112	0.246	0.090
April		0.134	- 0.021
July			- 0.155

The accuracy of DTS measurements is therefore lower than expected, at least with the instrument and the measurement protocol used for this study. Very high accuracy can be reached by continuous measurement (Allard, pers. com.), but is limited for periodic measurements with short acquisition times. It could possibly be improved by increasing the measurement time, but in high alpine field conditions this is limited by the power supply and, in winter conditions, by the freezing of the calibration bath.

3.3 Calibration of the DTS measurements

The DTS technique provides relative temperature measurements, and needs to be calibrated in order to allow the conversion into absolute values. Theoretically, and under standard temperature conditions of the DTS unit, the calibration is dependent on the characteristics of the optical fiber only, and needs to be done only once. The offset to true values should remain constant. Practically, our measurements show that the offset is not constant. This is due to the fact that signal intensities are compared to an instrument internal reference which can be subject to the influences of ambient temperature, certainly an issue in low temperature alpine conditions. The offset appears to be the same on a given day and for both measurement directions, but varies by several degrees between different measurement sessions. Between the 2011 and 2013 measurements, changes were made to the optic fiber, namely the replacement of the connectors, which obviously explains the offset shift. Otherwise, changes in the offset are due to ambient and instrument temperature and the quality of the fiber connections at the plugs to the instrument. Thus, every DTS measurement needs to be calibrated independently, and the offset cannot be transferred from one measurement to another.

An alternative to the slush bath is the use of a classical sensor, ideally below the ZAA depth, as reference temperature for calibration. This method was applied to our measurements by adjusting all profiles to the readings of the thermistor at 29 m depth which was considered a reliable sensor. Results are comparable to the slush bath calibration. This method, however, relies entirely on the accuracy and stability of the reference sensor used.

3.4 Comparison of DTS with classical thermistors

Given all the above mentioned conditions, DTS measurements can be compared to the classical sensor measurements. Unfortunately, several sensors failed, so that the comparison can not be made on the whole profile. The sensor profile shows three warm intervals with values close to or at 0°C : at depths of 40-45 m, 60-70 m, and on the two lowermost sensors, at 95 and 100 m. The DTS profiles, however, show no temperature anomaly at these depths. These values are thus most probably due to defective sensors.

The accuracy of DTS measurements is similar to that of the PT100 sensors, even when averaging all four profiles of a measurement run, or several measurement runs for the stable section below ZAA depth. The match of

DTS and valid electronic sensor values is always within the measurement accuracy, and validates the DTS results.

3.5 Detection of sensor failures and drifts

As mentioned above, the DTS profiles provided clear evidence that the values of the sensors at 40-45, 60-70 and 95-100 m do not indicate a talik nor the permafrost base, but result from an abnormal deviation of the sensors. The plastic bag used on the aerial part as length marker shows that a temperature deviation even on a short length (30 cm) induces a clear peak in the DTS profile. Thus the absence of a warmer signal on the DTS profile at 40-45 m, 60-70 m and at 98-100 m can not be explained by a smoothing of the DTS signal, but represents the right temperature values.

A combined installation of a sensor chain and DTS can therefore be used for detecting inconsistent sensor values. DTS could be also used for the detecting of sensor drift, but with the limitations due to its lower accuracy.

3.6 Technical and logistical issues

The DTS technique has a very low installation cost, but the total cost can increase if technical issues arise. The fiber optic cable itself was actually very cheap (less than ca 400 € for a 700 m long fiber, with connectors). However for the case presented here, the connectors had to be changed twice and the fiber needed repair on the spot after its installation. The splicing of a 25 µm fiber is a high precision task, and the splicing instruments are very sensitive to air pressure and temperature. The realizing of a splicing at high altitude and/or in cold winter conditions requires special skills and specially adapted equipment. Only one company was able to do the reparing job in these conditions. The total final cost was thus much higher and it approaches that of a sensor chain.

Another limitation is related to the cost of the instrument. Most of the standard instruments available on the market work only with positive air temperature. We had to choose an instrument made for measuring even in cold, below zero conditions. Such instruments are very expensive. It was not affordable to leave the instrument on the field for continuous monitoring. DTS proved therefore to be best suited for periodic short duration measurements, but with a limited accuracy.

4 CONCLUSION

The 2Alpes-3065 borehole provides a 100 m deep temperature profile of perennially frozen bedrock at 45°00'00'' latitude in the French Alps. The temperature at zero annual amplitude depth is -1.3°C, and the bottom temperature is -0.7°C, indicating that the permafrost at this site, at 3065 m elevation, is more than 100 m deep.

The combination of redundant sensor systems for the measurement of permafrost temperatures, a traditional thermistor chain and a fiber optic cable for Distributed Temperature Sensing (DTS) permitted to compare the performance and the advantages and shortcomings of classical borehole measurements with the recently established DTS technique in environmental sciences. The conception of the installation provides four parallel DTS profiles which can be compared,in order to assess the overall accuracy in the temperature measurements. The results show a good agreement of the two techniques, within the relative measurement uncertainty. However, the DTS shows a lower accuracy than expected, and needs independent calibration of each measurement when used for periodical measurements. It has to be noted that the DTS instrument used in this experiment was a quite old one (2007), and that a much better accuracy could be expected from the most recently available units and from future generation instruments.

Nevertheless, DTS proved to be a valuable tool for permafrost borehole temperature measurements. It provides continuous temperature profiles at 1 m resolution, whereas traditional thermistors are usually spaced at 5 to 10 m. The comparison permitted also to detect thermistor failures and to exclude the hypothesis of the presence of a possible talik at the experimental site. As there is no need for continuous measurements of temperature profiles in the deep permafrost, we can conclude that the best instrumentation for borehole temperature measurements would be a combination of classical thermistors for monitoring of the upper section down to ZAA, and DTS for periodic measurements of the lower section of the borehole.

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