

Environmental temperature sensing using Raman spectra DTS fiber-optic methods

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[1] Raman spectra distributed temperature sensing (DTS) by fiber-optic cables has recently shown considerable promise for the measuring and monitoring of surface and near-surface hydrologic processes such as groundwater–surface water interaction, borehole circulation, snow hydrology, soil moisture studies, and land surface energy exchanges. DTS systems uniquely provide the opportunity to monitor water, air, and media temperatures in a variety of systems at much higher spatial and temporal frequencies than any previous measurement method. As these instruments were originally designed for fire and pipeline monitoring, their extension to the typical conditions encountered by hydrologists requires a working knowledge of the theory of operation, limitations, and system accuracies, as well as the practical aspects of designing either short- or long-term experiments in remote or challenging terrain. This work focuses on providing the hydrologic user with sufficient knowledge and specifications to allow sound decisions on the application and deployment of DTS systems.

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1. Introduction

[2] The use of heat as a tracer in hydrologic systems has a long and successful history. Both the temporal and spatial distribution of fluid temperature (either as a surrogate for or input into energy conservation formulations) has provided process insights from deep in the crust to the atmosphere. Tracking thermal pulses, estimating fluid fluxes, tracing surface water–groundwater exchange, and predicting groundwater recharge have all benefited from the study of thermal signatures (the reader is referred to *Anderson* [2005] and *Stonestrom and Constantz* [2003] for thorough reviews and analyses of thermal methods in near-surface hydrology). Measurement systems have ranged from handheld mercury thermometers to forward looking infrared imagery and typically provide either a “point-in-time” measurement across a landscape or borehole or, alternatively, a “point-in-space” measured over a time span. As a result, thermal measurements are often spatially or temporally constrained, and few approaches are available to provide coverage both in space and in time.

[3] The Raman spectra distributed temperature sensing (DTS) for use in hydrologic applications presents an opportunity for continuous interrogation of streams, catchments, lakes, the atmosphere, and the oceans. These temperature-sensing systems were first developed in the 1980s [e.g., see *Dakin et al.*, 1985; *Kurashima et al.*, 1990] and were utilized primarily for fire monitoring, pipeline monitoring, and other industrial applications. While reports of DTS applications in geothermal wells first appeared in the mid-1990s to late 1990s [*Hurtig et al.*, 1994; *Sakaguchi and Matsushima*, 2000], it is only since 2006 that hydrologic applications have employed dedicated installations rather than opportunistic use of existing communication cables [*Selker et al.*, 2006a, 2006b; *Westhoff et al.*, 2007; *Lowry et al.*, 2007; *Henderson et al.*, 2008; *Moffett et al.*, 2008]. For example, Figure 1a shows a time series of vertical temperature measurements taken through the thermocline at Lake Tahoe in northern California on 7 June 2007. At each time slice (1 min), over 400 temperature measurements were made through the water column by suspending a fiber-optic cable and interrogating it from the surface. Figure 1b shows only the upper 100 m of the profile to highlight the thermocline interface. The oscillations that can be seen in the thermocline (for example, between 30 and 40 m depth) at a frequency of $\sim 10^{-3}$ Hz may be the result of internal gravity waves traversing the lake after several days of high winds. The internal gravity waves propagate along the thermocline interface, where the vertical gradient in water density (due to surface heating) is greatest. With a 1-min integration time, the temperatures are resolved to $\sim 0.1^\circ\text{C}$ over each meter of fiber. Unlike thermistors or thermocouple strings suspended at fixed depths sampling in time or conductivity-temperature-depth casts at high vertical

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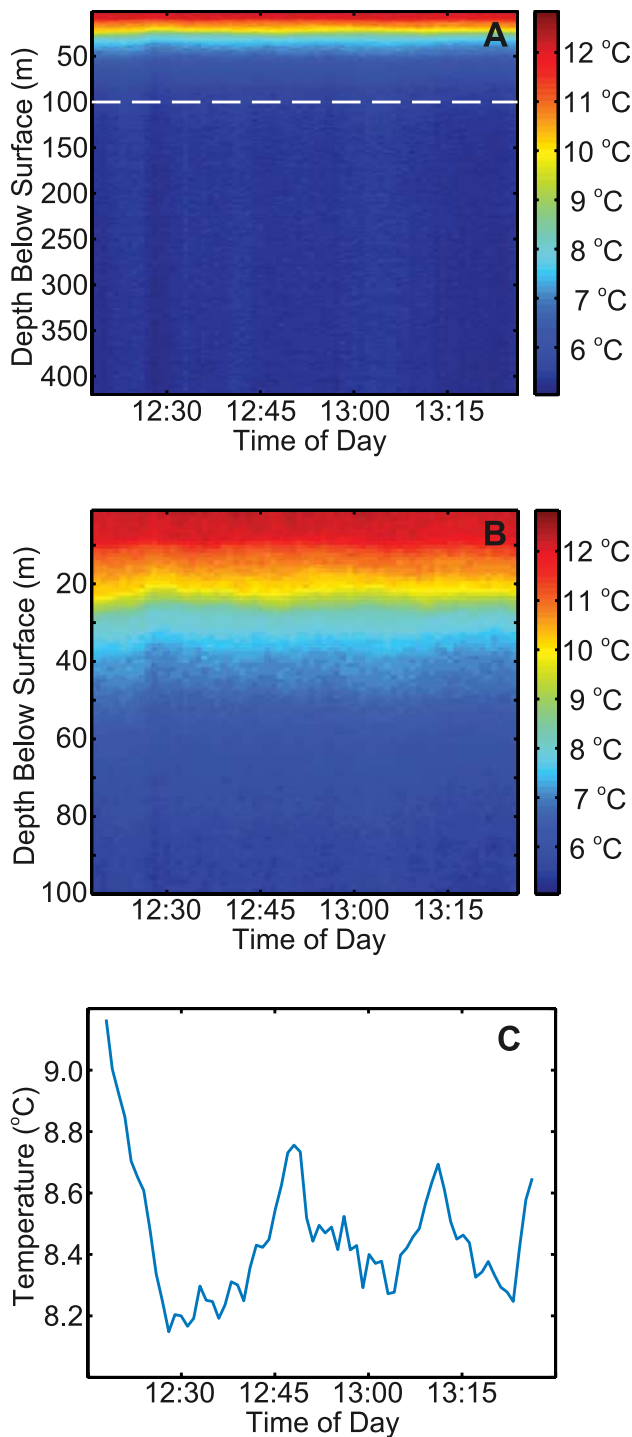


Figure 1. Time series of water column temperatures collected from a 420-m fiber-optic cable suspended from a research buoy to the bottom of Lake Tahoe (~ 430 m) on 7 June 2007. (a) The entire depth profile displaying a strong thermocline at ~ 20 – 40 m and constant (in time and depth) profile of bottom waters. (b) An expanded view of the upper 100 m of the profile, suggesting a record of temperature fluctuations in the thermocline (clearly visible at 25–35 m depth) consistent with internal gravity waves generated from a series of storms several days before the measurements were made. (c) The time evolution of temperature at a depth of ~ 27 m below the water surface, displaying a periodicity of ~ 25 min.

resolution but without repeating in time, DTS offers an unparalleled spatial and temporal-sampling resolution for many hydrologic applications.

[4] Previous work has thoroughly described the theoretical basis and physical design of commercially available DTS systems, and the reader is referred to *Selker et al.* [2006a] for more details. DTS is not, however, without complications and requires significant initial investment and careful experimental design to produce at its capacity. The primary objectives of this work are (1) to provide the readership with knowledge of the practical aspects of DTS and DTS experiments in hydrologic applications and (2) to assess limitations and uncertainties that must be addressed to fully utilize these systems for hydrologic measurement. The manuscript begins with a review of DTS theory, followed by an assessment of the accuracy and precision of the instruments that can be expected for hydrologic applications, and concludes with practical experimental design considerations for the deployment of the instrument-cable system. Application of DTS in environmental sciences is a rapidly evolving field, and we hope that this discussion will provide guidance for the use of DTS in hydrologic applications.

2. Assessing DTS Systems for Hydrologic Measurement

2.1. DTS Instrument Considerations

[5] Effective application of DTS to environmental sensing requires appreciation of the physics of the measurement, which provide context and criteria for instrument and cable selection, deployment design, and calibration methods. Because these choices determine the quality of the data collected by the DTS instrument during the experiment, they must be made in light of the goals of the experiment, the theoretical and physical limitations of the technology, and the physical limitations of the field deployment, including cost.

[6] To measure temperature in the fiber, the instrument pulses a laser and times the return signal. Finite measurement speed and dispersion of light along the fiber imply that Raman spectra DTS systems measure the average temperature along a length of the fiber-optic cable, typically 1–3 m, rather than at a single point. Commercial DTS systems use a variety of signal generating and processing schemes, including time domain, frequency domain, and spread spectrum modulation. With the speed of light in the fiber known, it is possible to calculate the source of the Raman scatter within 1 m for cables up to 5 km and on the order of 1.5 m for cables up to 10 km in length because of the intrinsic dispersion of the multimode fibers employed in the method. Achieving this spatial resolution requires truncation of the signal. For example, most commercial fibers have an index of refraction close to 1.5, so the speed of light in the fiber is about 0.2 m/ns. Since the backscattered arrival includes the two-way travel time, the delay from the instant of light injection to observation of the backscattered arrival is approximately 10 ns/m, with the backscatter from any particular meter arriving spread out over a 5-ns period. To avoid temperature distortions due to dispersion of light within the fiber, the first and last 1–2 ns of the pulse return must be trimmed. This leads to greater signal loss for finer

spatial resolution: assuming a 1-ns trimming, 1-m resolution loses 40% of the signal (2 ns of the 5-ns signal), while 2-m resolution would lose only 20% (2 ns of a 10-ns signal). The bandwidth capacity of the fiber itself can also affect the spatial-resolving ability of DTS. In addition, the sampling rate of instruments (limited by the circuit-processing speeds used by each instrument) can lead to additional signal loss at high spatial resolution. A longer spatial-averaging interval can significantly improve the quality of the DTS temperature measurements, so spatial averaging should always be selected with care in accordance with the experimental requirements.

[7] DTS temperature measurements employ the amplitude ratio of the amplitudes of the backscattered Stokes to the anti-Stokes signals [Selker *et al.*, 2006a]. The Stokes and anti-Stokes signals are the result of the Raman effect, in which incident light interacts inelastically with the electrons in the molecular bond. The molecule will emit light (scatter) light at two characteristic frequencies (Stokes referring to light of lower frequency and anti-Stokes returning light of higher frequency), reflecting the quantum energy states of the electrons which the photons encountered. The higher the temperature, the greater will be the number of electrons in high-energy states, increasing the fraction of anti-Stokes scattering relative to the Stokes signal. The ratio of these signals provides a quantity independent of light intensity that depends only on the temperature of the fiber at the location identified by the two-way travel time of light since the time of injection. Since only a small fraction of the incident light is scattered in an optical fiber, signal strengths are very low, which is the primary limit on the precision of DTS measurement. Greater signal strength may be achieved by longer integration time (summing the ratios obtained from a large number of pulses), brighter lasers, or spread-spectrum modulation. Temperature resolution approaching 0.01°C is possible with long integration times if the DTS device itself is protected from changes in temperature [Selker *et al.*, 2006a].

[8] The time-averaging interval is also an important consideration in experimental design. Fundamentally, the precision of the method is a function of the Stokes to anti-Stokes backscatter ratio precision. Since this factor is proportional to the number of photons collected by the detectors (linear in time), the precision of this ratio follows the central limit theorem and thus is proportional to the square root of time. All other things being equal, a longer time-averaging period will provide a more precise temperature measurement.

[9] Hydrologists need to understand the anticipated repeatability and accuracies that can be expected from DTS in order to adequately design, logistically plan, and financially budget installations. As DTS systems measure temperature as a function of both space and time, it is important to clearly define repeatability, accuracy and resolution. Taylor and Kuyatt [1994, p. 14] define repeatability as “closeness of the agreement between the results of successive measurements of the same measure and carried out under the same conditions of measurement.” To evaluate repeatability, Taylor and Kuyatt [1994] suggest the same measurement procedure, observer, instrument, and location. Furthermore, the measurements must be repeated over a short period of time. By statistically examining the

dispersion of the repeated measurements, the repeatability of the measurements can then be quantified.

[10] Repeatability is important for hydrologic applications; however, absolute accuracy, or the ability to measure a temperature accurately, is also an important factor in designing a DTS deployment. Absolute temperature accuracy is typically referenced to a standard measurement method, such as standard platinum resistance thermometers. For most commercial DTS systems, manual calibration against such standard thermometers can easily be used to develop accuracies of $\pm 0.1^\circ\text{C}$ or better. Typical DTS calibration procedures are discussed further in this work.

2.2. Repeatability

[11] We have chosen to adapt the concept of Taylor and Kuyatt [1994] for our typical conditions and divide repeatability into two components: temporal and spatial. Temporal repeatability may be an important limiting factor in the accuracy of long-term DTS system deployments. Many hydrologic experiments rely upon long time series data records, in which the evaluation of a time-varying signal leads to conclusions about a given hydrologic system. The temporal repeatability (including instrument drift) can be evaluated by monitoring a section of fiber held at constant temperature (for example, in an ice bath at 0°C or any known and unvarying temperature environment) and subjecting the instrument to environmental stresses such as varying instrument temperature, as would typically be found in field installations. Spatial repeatability quantifies the ability of a system to correctly interpret a sequence of temperatures in space. For example, when DTS systems are deployed in streams to detect groundwater inputs [Selker *et al.*, 2006b; Westhoff *et al.*, 2007; Lowry *et al.*, 2007], it is necessary to understand the instrument’s ability to detect the spatial patterns of stream temperature and its reliability to do so.

[12] A series of controlled field trials in the deep waters of Lake Tahoe were conducted in June 2007 to assess both the temporal and spatial repeatability of several DTS systems. Three manufacturers supplied DTS instruments for the testing (Agilent Technologies, Inc.; Sensornet, Ltd.; and SensorTran, Inc.). Data presented here are not designed to evaluate the merits of one manufacturer over another, as the optimal operating conditions are dependent not only on the DTS instrument but also on the software used and on the fiber-optic cable. As such, the instrument numbering (1–3) does not necessarily correspond to the order given above. These data are instead shown to illustrate the range of repeatability and spatial resolution that is commercially available today. For these tests, the three DTS instruments were brought aboard the University of California, Davis research vessel *John LeConte* and were deployed at a monitoring buoy located in the north portion of Lake Tahoe in ~ 430 m of water. A loop of BruSteel[®] fiber-optic cable (Brugg Kable AG, Brugg, Switzerland) containing two multimode fibers encased in a sealed stainless steel capillary and covered by wire rope and a PVC jacket was lowered to within 10 m of the bottom and was looped back to the surface. This fiber, along with all fibers used in the testing program reported here, was terminated with E2000 connectors, the general industry standard for fiber-optic connections for DTS applications.

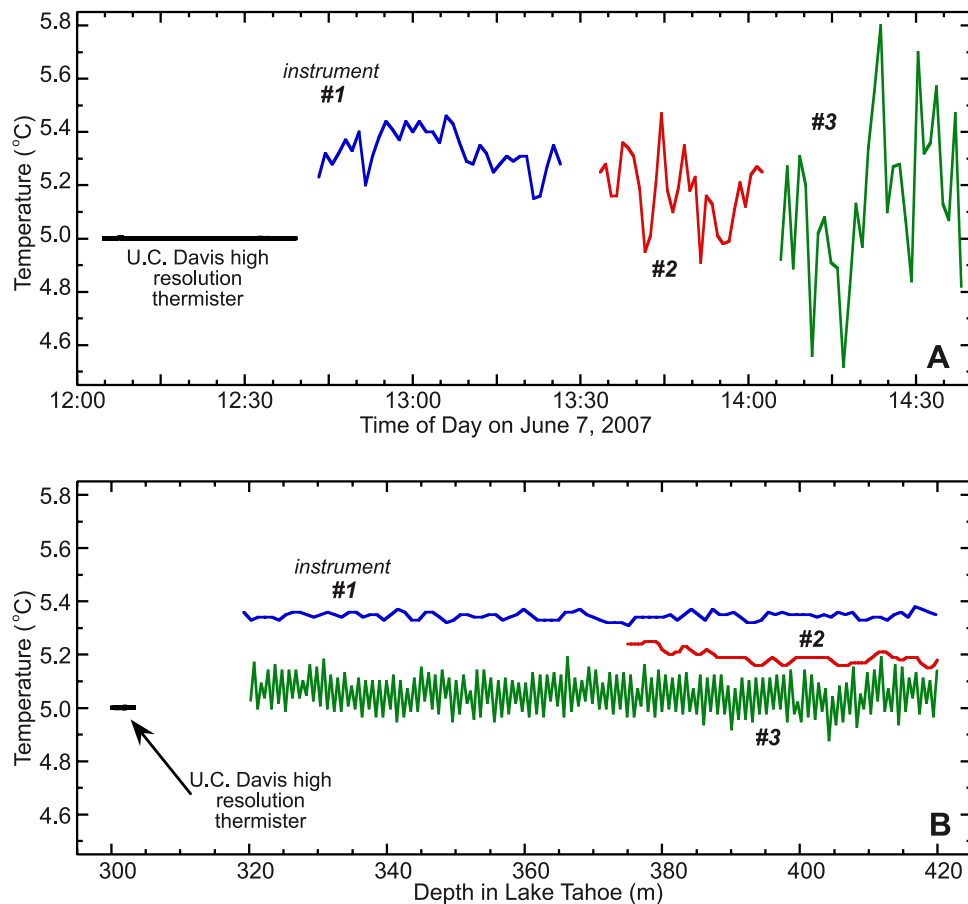


Figure 2. Field repeatability test results of three DTS systems in the deep waters of Lake Tahoe, California: (a) time series from a single depth (~ 400 m) and (b) average (~ 30 min) vertical distribution of temperatures over a deep portion of Lake Tahoe, where temperatures were unchanging.

[13] The temperature profiles taken during this experiment show a thermocline approximately thirty meters below the surface (Figure 1a), with near-constant temperature below the thermocline. Thermistor measurements (Figure 2) taken at a depth of approximately 302 m show a constant water temperature of $5.002^{\circ} \pm 0.002^{\circ}\text{C}$ over a 30-min period just prior to the deployment of the fiber-optic cable and DTS measurements. Taking advantage of this constant temperature of the deep lake water, it is possible to demonstrate both the temporal and spatial repeatability.

2.2.1. Temporal Repeatability

[14] Figure 2a shows the temperature time series for the three different instruments taken at a depth of ~ 400 m. The time series was collected within a 2-h period, during which there was no change in the independent thermistor-measured temperature at these depths. Because of the small diameter of the cable, it quickly reached thermal equilibrium with the surrounding fluid. Instruments 1, 2, and 3 showed mean temperature readings of 5.33° , 5.18° , and 5.14°C , respectively, slightly higher than the independent thermistor measurement. This was likely due to the calibration bath used for each of the DTS instruments, which only had ~ 5 m of cable immersed in an ice bath. The short calibration section was the result of logistical challenges on the vessel and would generally produce a calibration offset that was neither

accurate nor appropriate for each instrument. An ideal calibration uses a longer length of cable, typically 30 m or more, at a known constant temperature to determine the offset of the temperature measurements.

[15] Despite the inaccurate calibration, the temporal repeatability of the three systems is quite good, with temporal standard deviations of 0.08° , 0.13° , and 0.31°C , respectively, for the three instruments shown. The temporal repeatability was consistent throughout the deep waters for each of the instruments tested on this particular fiber-optic cable but was somewhat elevated when the instruments were connected to a “well-used” cable that contained several step attenuations resulting in less signal returning to the sensors. The impacts of cable flaws/damage on data quality will be discussed in subsequent sections.

[16] It is important to note that these tests were conducted over fairly short time durations (2 h) and that the long-term stability of the measurements was not tested. We have noted larger ($\pm 1^{\circ}$ to 2°C) instrument drift when DTS instruments are deployed for multiday experiments and, in particular, when the instruments are subjected to significant internal temperature variations. The long-term stability can be improved using a dynamic calibration method available on some DTS instruments, and the importance and source of long-term drift is the subject of ongoing work.

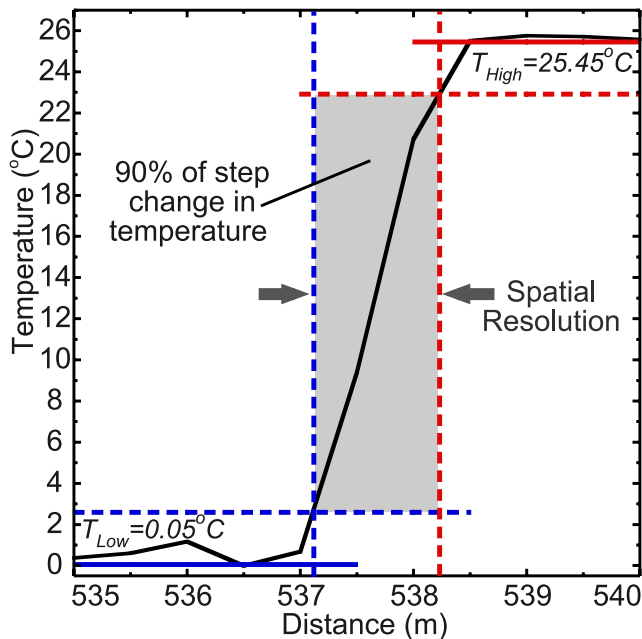


Figure 3. Illustration of the spatial-resolution calculation for a single trace (with instrument 2 on 4 June 2007 at 1640:07 local time) from the laboratory testing described.

2.2.2. Spatial Repeatability

[17] The spatial repeatability of measurements was examined along a length of fiber at uniform temperature from traces taken over a specified time interval (we define a trace to be a single temperature versus distance graph). Spatial repeatability is an important consideration in stream-groundwater studies, where changes downstream in water temperature are used to infer groundwater inputs. It is much easier, for example, to immerse a long section of fiber in a well-mixed constant temperature bath than to maintain that bath temperature constant over long periods of time, particularly under field conditions. Spatial repeatability is quantified by taking the standard deviation of a number of consecutive measurements over a given length of fiber at a constant temperature during a single trace of the DTS instrument.

[18] Figure 2b shows the 30-min averaged temperatures of the bottom ~ 100 m of the lake for each of the tested instruments. Once again, the absolute accuracy was affected by the less than ideal temperature bath; however, the spatial repeatability for all three instruments is quite good with spatial standard deviations of 0.02° , 0.04° , and 0.08°C , respectively. The high-frequency spatial variability visible (sawtooth pattern) in the signal of instrument 3 may be partially the result of this instrument's sampling resolution/spatial resolution algorithm. It is clear, however, from Figure 2b that small changes in temperature over space can be easily resolved with DTS.

2.3. Resolution

2.3.1. Spatial Resolution

[19] The spatial resolution of a DTS system is also an important consideration for hydrologists and refers to the spatial integration scale over which a single value of temperature is reported. Most DTS instrument manufac-

turers state a minimum spatial resolution (on the order of $+1$ m), and this resolution can be adjusted upward in many instruments if coarser-scale measurements are more appropriate. In testing the spatial resolution of a DTS system, the length of fiber required to display a known step change in temperature along the fiber is determined. A simple laboratory setup was constructed using a single ice bath to examine the defined spatial resolution twice for each instrument (into the bath and out of the bath representing two "steps"). We define in this work the "spatial resolution" of the DTS system as the length of fiber required to show 90% of the known temperature change (note that other definitions of spatial resolution commonly reported use a definition of 80% of the temperature change). The temperature change is calculated from the difference between the two reference temperatures. For example, if the bath temperature change is from 25° to 0°C , the spatial resolution is the distance over which the DTS temperature measurements change from 23.75° to 1.25°C , i.e., 90% of the total temperature change centered on the mean of the two constant temperatures. Figure 3 shows one example trace of the spatial resolution testing in which the fiber is exiting an ice bath.

[20] The spatial resolution test will be affected by the spatial-averaging design of each DTS instrument, and the spatial resolution test is intended to quantify these effects. To ensure that the test is accurate, a length of fiber must be maintained at a constant temperature on each side of the step change. We recommend a minimum length of 10 times the spatial-averaging interval of the DTS system being tested.

[21] A total of 60 time slices for each instrument was used to evaluate the spatial resolution. The fiber-optic cable used in the experiment used connectors that showed higher losses than that normally expected (higher than normal connection loss results in less return signal and lower resolution). Using the defined 90% step change, instrument 1 demonstrated a mean spatial resolution (over 60 tests) of 3.35 m with a standard deviation of 0.50 m; instrument 2 showed a spatial resolution of 1.91 ± 0.27 m; and instrument 3 returned a spatial resolution of 3.45 ± 0.39 m. These spatial resolutions are ~ 2 – 4 times that reported by the instrument manufacturers (instrument 1, 1 m; instrument 2, 1.5 m; instrument 3, 1 m) and reflect both differences in laboratory conditions and testing methodology and the use of low-quality fiber and connectors in this particular test. These results suggest that spatial resolution of DTS systems needs to be tested for individual applications and specifically for those fiber-instrument combinations used in the field to adequately quantify the spatial resolution that can be obtained.

2.3.2. Temporal Resolution

[22] The temporal resolution of a DTS system is typically controlled by the instrument's ability to statistically measure the returning Raman energies, which are both low in amplitude. Most commercially available DTS systems can resolve fiber temperatures over 10-s intervals and are sufficient for many rapidly changing hydrologic systems. As the sampling time is increased, the resolved temperatures become more accurate. However, longer temporal averaging reduces the probability of detecting a rapidly changing temperature signal. Because postcollection averaging of

short sampling intervals provides the same statistical reduction of variance as one longer sampling interval of the same time, one should always choose the longest averaging time that still assures sufficient temporal resolution to satisfy the environmental-monitoring objectives of the study. Given the very low cost of data storage, it is strongly advised to carry out postcollection averaging rather than averaging during data collection, since any averaging done by the instrument cannot be reversed.

[23] Temporal resolution is also profoundly affected by the choice of fiber-optic cable. Small-diameter cables using low heat capacity coatings and strength elements will respond more quickly to environmental temperature changes than will heavily armored and large-diameter cables. For many of the fiber-optic cables deployed to date in hydrologic applications, the time scale for the cable to respond to thermal changes is still quite short (typically on the order of seconds to 1 min), and it is important to conduct simple step change heating/cooling experiments to insure that the fiber used is compatible with the anticipated time scales of environmental temperature change.

2.4. Cable Options and Instrument Operation, Design, and Performance

[24] Researchers contemplating DTS systems for hydrologic experiments need to consider the installation as a total system which includes fiber-optic cable design, configuration, and environmental constraints. In this section, we focus on “downstream” aspects of DTS, i.e., those components of the system such as the fiber-optic cable and connectors that transmit signals and affect signal quality.

2.4.1. Cable Options

[25] The package of properly protected optical fiber(s) is referred to as the cable, which will include tensile strength members, physical armoring protecting the enclosed fiber from impingement, and a water-tight barrier to eliminate all chemical contact with the glass. It is very common for a cable assembly to contain several fibers, both for redundancy and for larger bandwidth. There are many cables currently available on the market today, so it is important to consider the experimental environment and potential stresses on the cable before making an investment. Typically, less than 10% of the cost of a cable suitable for field deployment for environmental sensing is attributable to the fiber itself. The fiber must be protected from potential damage, often including debris (e.g., rocks in rivers or falling branches in forests), animals, and pressure (in deep water). The specific construction of cable containing fibers is important depending on the conditions in which the cable will be deployed.

[26] Optical fibers used for Raman DTS typically consist of a 50- μm diameter glass core surrounded by a 37- μm glass cladding that creates a reflective boundary by way of a change in index of refraction. The transition in optical properties between the core and cladding glass can be a gradual graded index or abrupt step index. For sensing at temperatures below 150°C, graded index fibers are preferred because of lower optical dispersion, while at elevated temperatures, or for applications with many tight bends, the step index fiber should be used.

[27] Immediately surrounding the fibers are protective materials (buffering) which fall into two categories: loose tube and tight buffered. The loose tube construction sur-

rounds the fiber with a hydrophobic gel. The gel protects the fiber from exposure to water, as contact with water can lead to hydrogen contamination of the fiber, compromising the index of refraction step function in the fiber package and thus leading to light loss. In addition, the gel-filled capillary helps physically isolate the fiber from damage due to mechanical impingements. The loose tube fiber and gel are housed within capillaries made from plastic or stainless steel, capable of providing protection sufficient for pressures found on the ocean floor and vehicular passage over cables on hard surfaces. Tight-buffered fibers have an injection-molded plastic coating protecting the fiber. These coatings provide excellent control of hydrogen diffusion and protection from mechanical abrasion, but any force applied to the outside of the buffering results in strain on the glass fiber. In general, tight-buffered cables should be avoided for environmental temperature sensing applications, though acceptable data may be obtained with care.

[28] Tensile stress must also be avoided, and two measures are typically taken. In loose tube buffering, the fiber is “overstuffed” so that if the cable experiences limited elongation (<1%), the fiber will not become strained. Second, aramid or other high-strength materials are often incorporated in a cable to further protect the fiber from elongation. Cables are often sheathed in a plastic jacket, which should be selected to withstand anticipated exposure to sunlight or expected mechanical insults. Cables can often be ordered with printed distance markings to aid in georeferencing. Specially fabricated cables may also include components such as electrical conductors or reflective coatings to minimize the impact of solar radiation on the cable temperature. Highly protected cables can be expensive (>\$10/m) and quite heavy (>30 kg/km) and more difficult to handle than a less robust cable; they will also have a greater thermal inertia than lighter cables and will thus respond more slowly to temperature changes in the environment.

[29] As light passes down the fiber, is scattered, and returns to be detected, some light is lost or attenuated uniformly along the fiber. Attenuation is defined as the loss of signal per unit length of fiber and is a function not only of fiber construction but of wavelength of signal. Standard telecommunications fibers used for environmental DTS have quoted losses of ~ 0.3 dB/km (at standard telecommunications frequencies) which can be quantified during DTS calibration to determine the appropriate correction factors. However, other factors can lead to much higher, localized attenuation, including tensile stresses, hydrogen gas penetration, air gaps in junctions, and bend angles exceeding the internal angle of refraction. Typically, fiber bend radii of less than 2.5 cm should be avoided, but for short cable lengths, this can be reduced.

[30] Simple attenuation typically results in a noisier temperature signal, as less light is returning to the detector per unit time. However, as DTS temperature is calculated from the ratio of Stokes and anti-Stokes returning signal, attenuation that affects these two signals differently will lead to incorrect temperature calculations. Unfortunately, most attenuation processes are wavelength-dependent, and therefore, the difference in attenuation of these two signals, termed differential attenuation or DA, is a very important factor in the accuracy of DTS-derived temperatures. Fortunately, experimental geometry, internal DTS algorithms,

Table 1. Comparison of Single- Versus Double-Ended DTS Measurements

Location	Single-Ended σ^a (°C)	Double-Ended σ^b (°C)
Near ice bath (3.5–26.5 m)	0.26 ± 0.05	0.47 ± 0.08
Far ice bath (1061–1084 m)	1.2 ± 0.18	0.65 ± 0.10
Cable midpoint (531.5–556.5 m)	0.39 ± 0.06	0.31 ± 0.05

^aValues are the mean and standard deviations of 87 single-ended traces.

^bValues are the mean and standard deviations of 87 double-ended traces.

and even multiple laser sources can be designed to minimize and/or correct for differential attenuation. The ubiquitous presence of DA requires use of known temperature baths at each end of each cable section free of connectors or fusion splices.

2.4.2. Instrument Options and Performance

[31] An important decision for DTS cable deployment related to the impacts of differential attenuation is whether to use single- or double-ended measurements. Each has complementary advantages which may advocate the use of each for different experiments. Single-ended measurements refer to temperatures calculated from light transmission in only one direction in the fiber (analogous to a one-way, dead-end street). Single-ended measurements are most precise near the instrument and degrade with distance. Double-ended measurements are made by convolving single-ended measurements made from each end of a loop of cable with both ends of the fiber connected to the instrument. In a double-ended measurement, the temperature reported for each point incorporates data from traces taken in each direction, yielding greatest noise at the points closest to the instrument and least noise at the midpoint of the fiber. The advantage of the double-ended measurement is that it allows computation of the DA continuously along the cable for each measurement. For long-term monitoring or where the fiber has been or may be subjected to stresses/damage that lead to step or localized losses of light transmission, double-ended measurements will provide much higher quality data. Double-ended calibration typically requires only a temperature offset, whereas single-ended systems must be calibrated for differential loss, gain, and offset. Using a double-ended configuration, however, adds complexity to the system by requiring at least two input channels, twice the sensor length capacity and a doubling of the minimum measurement rate.

[32] Double-ended measurement geometries should not be chosen automatically for all applications, however, as they tend to add noise to resolved temperatures nearest the DTS sensor. To demonstrate the impacts of these two measurement approaches, both single-ended and double-ended traces were collected from a 1000-m cable deployed along the shallow littoral zone of Lake Tahoe. At both ends of the installation, 0°C ice baths containing 20–40 m of immersed cable were used first for calibration and subsequently for measurement of repeatability and accuracy. These reference baths were located close to the DTS instrument (termed “near ice bath”) and at the distal end of the installed fiber (“far ice bath”). Table 1 shows the average standard deviation of temperature through both ice baths. The mean standard deviation for the far bath in single-ended mode was almost 5 times greater than the near

bath, while in double-ended mode, the near and far baths’ standard deviation differed only slightly. However, it is important to note that the standard deviation of the near bath in the double-ended case is almost twice as large as that from the same bath in single-ended mode. The use of a double-ended measurement in this case has degraded the signal near the DTS unit. This is the result of combining the two-way signals, which distributes the noise more equally along the length of the fiber.

[33] For applications where a uniform level of precision is needed along the length of the fiber, double-ended measurements will be preferred. If there is any chance of time-dependent differential attenuation, the double-ended measurement can provide data that might otherwise contain artifacts that would not be possible to remove [see Tyler *et al.*, 2008]. DTS instruments capable of double-ended measurement can typically be configured to alternate between single-ended and double-ended measurements, allowing for hybrid data collection. However, for sites where higher levels of precision are needed close to the instrument (for example, the data shown in Figure 1) or where it is not convenient to have a continuous fiber return to the DTS unit, single-ended measurements may be advantageous. An alternative approach to correct time-dependent DA is to add additional laser sources to the DTS instrument which specifically measure the loss as a function of frequency at the Stokes and anti-Stokes frequencies. Finally, several instrument manufacturers are now producing DTS systems that utilize two or more lasers tuned such that the Stokes frequency of one laser is very close in frequency to the anti-Stokes frequency of the second laser, and much of the differential attenuation can be eliminated. In all cases, it is therefore important for the researcher to carefully evaluate the environment, the most crucial locations of measurements, and the time scales of variation in order to most effectively deploy a DTS system.

2.4.3. Other Performance Factors

[34] Numerous other factors can affect the accuracy and repeatability of the signal from a fiber-optic cable. Connectors and connection quality can have a significant impact on signal quality. The cable connection to the DTS instrument and to other cables may be achieved by a variety of methods that are dependent upon the installation. The fiber-optic industry has many standard connectors, with the E2000 connection having been adopted by the DTS industry. To minimize backscatter of the injected light, the connectors used for DTS must be angle polished, which is not standard for the multimode fiber required and thus must be special ordered. Mechanical connectors are susceptible to scratches, dust on the connecting faces, poor alignment, and air gaps which together can cause signal loss that may be a function of temperature and direction of light transmission. The asymmetrical losses are particularly problematic in that they are not well characterized in the interpretation of double-ended measurements and can give rise to temperature anomalies due to asymmetric DA. Manufacturers report that standard connectors typically cause a signal loss of 0.1–0.2 dB in the fiber line, although those losses are measured using a different wavelength of light than is used for DTS systems. The quality of a fiber-optic connector can be quite variable, depending on the precision of the fabrication process used to build it, as well as the age and

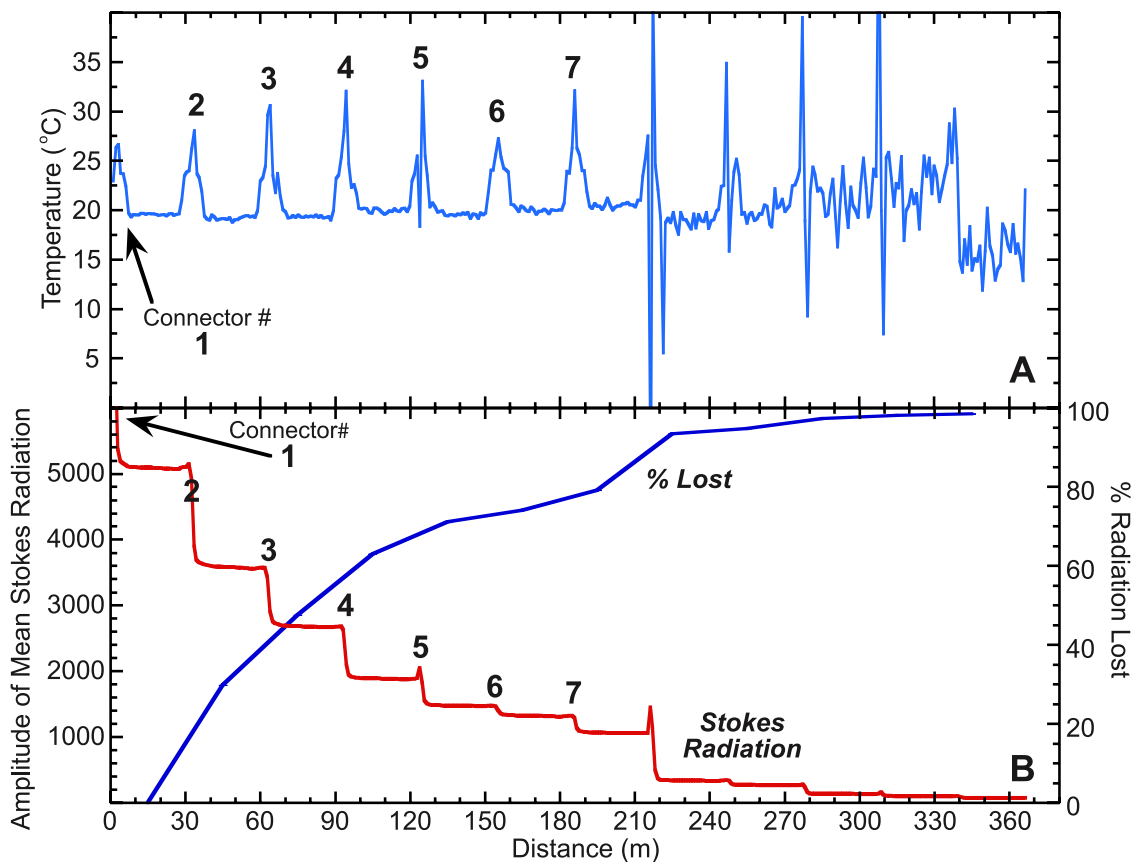


Figure 4. (a) Observed anomalies in reported temperatures at each connector (numbered points). (b) Magnitude of the returned signal (red, dimensionless) and of the signal attenuation (blue), which produces anomalous temperatures at each connector as a function of the number of connectors through which the light has passed. After eight connection passes, the signal amplitude of the returned signal is reduced such an extent that downstream temperatures cannot be resolved.

cleanliness of the connector itself. Unfortunately, some E2000 connectors purchased from different manufacturers have even been found to be physically incompatible.

[35] To assess the role of connector loss on data quality, a simple laboratory experiment was conducted through sequential connectors. A 21.5°C constant temperature bath was prepared, and a 30-m-long cable consisting of 12 fibers was submerged in the bath. At each end of the cable, connectors were used to join sequential fiber ends, resulting in a single cable effectively 360 m long with 12 connectors along its length. Results of this experiment are plotted in Figure 4. Each time the signal passes through a connector, there is a step loss in signal strength illustrated by the mean Stokes radiation (Figure 4b) averaged over the 10-min duration of the experiment. With each step loss in signal the variability of the calculated temperature in the constant temperature bath increases, with almost complete degradation of the calculated temperature after eight connectors (~210 m in Figure 4a). As seen in Figure 4b, half of the original signal is lost after passing through only three connectors, and the noise introduced through multiple connectors overwhelms the temperature signal after seven or eight connectors.

[36] Several alternative methods of mating fiber-optic cable for environmental applications are available. Mechanical splices use an index of refraction matching optical gel

to improve efficiency of light passage. Unlike the standard connectors, which require ends with connectors, mechanical splices can join bare, cleaved fibers. The closed splice clamps onto the buffer on each end of the fiber, providing strain relief for the exposed length of fiber inside it, and manufacturer's specifications report expected loss of 0.05–0.2 dB. However, we have found this low loss to be difficult to achieve in practice in the field, and such mechanical junctions have been seen to have temperature dependence in their DA, potentially leading to temperature offsets that are very difficult or impossible to fully eliminate.

[37] Ideally, one would prefer to join fibers with a continuous column of glass, which is what a fusion splicer produces. Like mechanical splices, fusion splices require cleaved, stripped fiber, and the two cores must be aligned to within $<1 \mu\text{m}$ of each other. The splicer brings the two ends together and then heats the aligned joint with a set of electrodes, fusing the two fibers into a single strand of glass. Because the fiber core and cladding are structurally weak, the joint must be handled carefully and must be protected from strain. Many commercially available fusion welders include an integral heater and standard heat-shrink sleeves that can provide strain relief and protection to the fused joint. A properly fused fiber typically has a loss of 0.01–0.03 dB.

[38] In a single-ended DTS measurement, the far end of the fiber should be correctly terminated. Because the DTS system relies on reflections to measure temperatures, the termination cannot be a cleaved cut. The flat surface of a clean cut reflects signals that can interfere with the instrument's temperature readings. A jagged break in the fiber is a better option because it does not efficiently return energy in a predictable manner. As an alternative to a cut or break that may reflect light, the far end of the fiber can be wrapped around a very tight radius (around a pencil, for example) such that the bend radius creates a larger angle of light transmission than the critical angle for total internal reflection and most of the light is lost. There are also commercially available terminations or attenuating fibers that minimize the signals returned to the instrument, eliminating potential interference and resulting in an improved data set.

2.5. Calibration Design and Requirements

[39] DTS systems must be calibrated to obtain accurate temperature data, with most DTS calibrations accounting for signal attenuation and temperature offset. Some instruments may also allow calibration for signal gain, but this is not typically a concern for environmental applications.

[40] The magnitude of the signal attenuation varies between cables but is usually constant within a single batch of fiber. In addition to the signal loss within the fiber, losses are introduced by connections and splices as well as any strains on the fiber. These losses may be permanent or transient and can be produced by physical impacts, sharp bends, or stresses applied to the cable. Some of these losses can be alleviated by adjusting the bend radius and strain relief in the cable deployment. When such adjustments are not possible, the loss must be included in the DTS calibration. In experiments like this, the calibration must be periodically checked to ensure that the magnitude of the loss does not change.

[41] To obtain the required information for calibration of a single-ended measurement, measurements must be obtained at two reference sections at two known temperatures. We have employed recirculating water baths, typically filled with water-saturated crushed ice (a "slush bath"), to provide constant temperatures for calibration. Because the DTS averages temperature over a length of fiber, it is important to have a sufficient amount of fiber in each bath to resolve a clear temperature measurement. We recommend a minimum of 10 times the length of the spatial sampling interval for the deployment. With two reference sections of fiber at known temperatures, the DTS calculates the differential attenuation (in dB/km) for the specified length of fiber. If an installation includes several sections of joined fiber, each section must be individually calibrated.

[42] In field applications, step attenuations will often be encountered along the length of the fiber. While calibrating the cable for each section of fiber, it is crucial to ensure that there are no step losses between the two reference sections. Individual step losses in the fiber, whether permanent or transient effects, are added to the calibration separately. Using a double-ended DTS configuration can greatly simplify calibration for signal attenuation, particularly step attenuations. Because a double-ended measurement "sees" the entire fiber from each end, the instrument can locate and quantify step losses as well as calculate the differential attenuation rate throughout the length of the fiber. While a

double-ended DTS deployment still requires some calibration to ensure accurate data, the loss calibrations can be computed for each meter of cable. Automated double-ended calibration algorithms are included in most DTS systems, though their performance is inconsistent. Since some instruments do not keep the base data from each of the two measurements, we recommend collecting the data from each direction and carrying out the double-ended corrections during data analysis. Additionally, since the double-ended approach requires the inclusion of data from two different measurements, each with its own intrinsic noise, temperatures computed from double-ended systems will always have greater noise than single-ended values. This can be very important when long, or high-loss, cables are used wherein the measurements near the DTS will incorporate measurements that reflect the entire loss of the full length of cable.

[43] The absolute accuracy of DTS measurements depends on correct calculation of the temperature offset, which accounts for instrument-specific sensor and laser performance. This value is easily obtained through the data employed in the single-ended attenuation determination, using one of the known temperature points as a reference to calculate an offset of the entire data set. A double-ended deployment requires a point of known temperature to calibrate for temperature offset.

[44] While all Raman-spectra DTS instruments can be calibrated for signal attenuation and temperature offset, a few instruments also provide calibration steps for signal gain. Changes in signal gain are the result of the greater temperature dependence of the anti-Stokes signal as a function of absolute temperature of the fiber and can affect measurements when a DTS is used to measure over large ranges of temperature, such as volcanic or geothermal settings. Calibration for gain requires reference lengths of fiber at two distinct known temperatures. In most hydrologic applications where temperature difference are less than $\sim 40^\circ\text{C}$, signal gain is typically not adjusted.

[45] Throughout the calibration procedure, it is essential to have a precision-calibrated thermometer as a reference. If independent temperature measurements are not feasible, at least two alternatives exist that can yield good calibrations. First, our tests have found that an insulated saturated slush bath made with low-salinity water can maintain a constant temperature of $0.07^\circ \pm 0.007^\circ\text{C}$ with care. This reference temperature can be used as the basis for calculating the temperature offset. In addition to the slush bath, many DTS units include a provision to attach an external thermocouple which can be used to provide this measurement as well. The thermocouple can be placed in an insulated area with a reference section of the cable, and the temperatures recorded by the thermocouple can be used as the basis for the temperature offset. This is further recommended as it provides a reference data set which will be recorded in the same files as the DTS data.

[46] We have found that long-term deployments of DTS systems can display drift in measured temperatures of up to several degrees Celsius (although typically $<1^\circ\text{C}$) along the entire length of the fiber, which can significantly degrade the quality of the data. This drift may be the result of changes in instrument temperature, changes in fiber attenuation due to changing stress conditions, or other sources.

This drift can often be minimized by the use of dynamic calibration, in which the instrument refigures the calibration constants for each trace. Dynamic calibrations require the use of either constant temperature slush baths or DTS systems equipped with independent temperature sensors. Alternatively, the inclusion of slush baths or other well-mixed temperature baths with either internal or independent temperature measurements during the entire period of measurement is very helpful in making trace-by-trace post-processing corrections to the offset. If it is not feasible to maintain a slush bath, a well-insulated water bath or even a well-mixed portion of a stream channel is almost as useful in this task as its temperature is likely to change very slowly, so any sudden changes reported for the temperature can be assumed to be offset errors. However, water baths can stratify, so it is important to colocate the cable and an independent temperature logger at the same depth in the bath to insure that the temperature of fiber is independently well known. The sources of instrument drift and techniques to reduce the potential for drift for long-term installations are an area of ongoing research.

2.6. Additional Experimental Considerations

[47] The DTS system (including fiber-optic cables) must also be designed to withstand the environmental rigors of the deployment. An important consideration in the design of a DTS experiment is the evaluation of the operating conditions. Many commercial DTS systems include an integral computer to operate the laser and to process the data internally; these instruments are generally rated to operate from 0° to 40°C. Computers require ventilation and may be damaged by dust or humidity inside the operating enclosure. Some instruments can operate without a computer, allowing operation in a wider range of temperatures and not requiring ventilation.

[48] Power supply often also presents significant constraints to DTS, though power requirements have dropped considerably in recent years. The lowest power systems currently available can be cycled to draw as little as 10 W, while the lowest-power continuously measuring systems draw on the order of 30 W. At current prices, solar power supplies for winter installations in the United States cost several thousand dollars and present significant exposure to vandalism in unsupervised locations. Some instruments have volatile memory, which can be problematic at sites with unreliable power. Other alternatives for remote installations include multiple batteries or gas-operated generators.

[49] Mapping the position of the DTS temperature measurements to actual physical locations in the study area, whether locations where the cable exits a stream, passes through a riffle pool, exits a borehole, or passes through any zone of interest, is often overlooked in the design phase but is crucial for correct data interpretation and comparison to other physical measurements. Experience has shown that the indelibility of cable markings is a goal rather than a reality, and continued reuse of cables in hydrologic applications will lead to eventual fading or loss of printed cable markings. Fortunately, a GPS combined with a portable heat source (or cold source, such as a bag of ice) is an effective means of ensuring registration of the geographic position along the cable to the DTS measurements. Physically securing the cable to insure a constant positioning is also important, particularly in fast-moving streams, and several

models of cable clamps using the telecommunications industry can be used for both strain relief and positioning. It is, however, critical that any securing system not impinge on the fiber or induce sharp bends in the fiber that would degrade the light signal.

[50] As with any temperature measurement, consideration of differential radiative heating/cooling must be evaluated. Care should be taken in very slow moving streams or in atmospheric installations, where solar heating of the fiber could result in higher than ambient temperatures being recorded. In typical stream environments where heat transfer between the water column and the fiber is convectively dominated, or in turbid water columns where radiation penetration is small, a small-diameter fiber can generally be assumed to be in thermal equilibrium with its environment.

[51] Finally, data acquisition and data management must always be considered in an experiment plan. Commercial DTS systems differ in their on-board data storage capacities and modes, communication options, and file structure. To date, most hydrologic installations have relied upon on-board data storage and manual data retrieval; however, direct Internet uploads can easily be accommodated by most systems. As large volumes of data are typically produced (both in time and spatially), data manipulation and presentation can present challenges. Most commercial DTS instruments are supplied with proprietary software to initially display DTS data. Commercial scientific computing software have typically been used to postprocess temperature data, and nonproprietary scripts to upload data from several of the most common DTS systems and related graphing scripts are maintained by the authors and are available upon request.

[52] Near-real-time data transmission and data display during deployment can be important in managing a DTS observational emplacement. A shallow stream deployment conducted by this group (not reported here) showed a localized increase in temperature that (with spot data visualization) might have been interpreted as a high-temperature groundwater input that was suspected in the region. However, detailed mapping of this location over a 24-h period showed that the temperature anomaly disappeared at sundown and reappeared at sunup, suggesting that the anomaly was the result of exposure of the black cable to sunlight in extremely shallow water. Near-real-time data transfer and some limited processing could have enabled this hypothesis to be confirmed prior to cable retrieval. However, as this deployment relied upon postrecovery data processing, the hypothesis could not be well confirmed. It is recommended that whenever possible, a degree of real-time data display and near-real-time processing should be conducted to maximize the results of any cable deployment.

3. Conclusions

[53] The use of DTS systems to quantify hydrologic processes offers significant advantages over traditional point-in-time or point-in-space measurements of temperature. The fiber-optic cable acts as a passive “thermometer,” and very large spatial domains can quickly and easily be covered in fiber-optic cable. The number of hydrologic applications is rapidly growing with DTS experiments beginning or contemplated in soils, the atmosphere, deep

boreholes and mines, lakes, glaciers, and the oceans. Laboratory and field testing have shown that commercially available DTS systems designed for industrial applications provide high-quality temperature resolution for many hydrologic applications. Their performance is strongly dependent upon the design of the experiment, operating conditions, choice of fiber-optic cable and connectors, and the level of training and competency of the operator. In a series of field trials, temporal repeatability was found to be somewhat degraded over that reported for DTS industrial applications or specified by the manufacturers; however, the temporal resolution matched or exceeded many traditional field hydrologic instruments. Spatial repeatability was very high and would generally exceed that used for many temperature/heat tracer experiments conducted in rivers and hyporheic studies. Long-term temporal repeatability of DTS systems remains an area of continued research and design, as many hydrologic applications may not provide the same level of environmental protection (buffered temperature, humidity, dust protection, etc.) that has been provided in industrial applications. However, these and other issues can be addressed with careful installation design and routine calibration.

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