sensors

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Temperature

Fiber Optics For Environmental Sensing

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Sensors

A staple of the oil industry, distributed temperature sensing (DTS)—capable of measuring temperature along a length of fiber-optic cable—is finding utility in environmental monitoring, helping researchers to tease out the hydrology of streams, air flow in valleys, and health of glaciers.

When was the last time that technology developed for "Big Oil" came to the rescue of the environment? The commercialization of distributed temperature sensing (DTS)—a sensing method that uses fiber-optic cables to measure temperature along the cable's length—has been driven primarily by a desire to increase oil well productivity. DTS is now becoming the darling of the environmental research community for taking the temperature pulse of the earth. The technology's outstanding temperature resolution in both space and time is filling gaps in understanding that have stymied research of complex ecological processes, supporting the well-worn truism that making better measurements is the first step to better understanding.

Out of the Oil Well, Into the Wild

In comparison to existing temperature sensors, the power of DTS is its combination of the ability to operate in extreme environments (such as those experienced down an oil well during drilling) with the ability to read temperature, at each location, over the entire length of the fiber-optic cable; reading up to tens of thousands of points at 0.01°C resolution.

An intense laser pulse is sent down the fiber and the fiber's temperature is computed from the light that is backscattered as a result. Although most of the light travels unimpeded, a small fraction of the light interacts with the glass, bouncing back toward the source—backscattering—and it is this faint optical echo that forms the basis for this sensing technology. The backscattered light has three wavelengths that we use: the wavelength of the injected light, that of the band just above, and that of the band just below this frequency (so-called Stokes and anti-Stokes bands). The ratio of the intensity of these two side bands reveals the temperature of the glass at the source of the backscattering. By determining the arrival time of the backscattered pulse we can determine the distance along the fiber that correlates with this ratio: for each 1 ns increase in arrival time, the source of the backscattered light is a foot further along the glass fiber. By recording the spectral distribution of the backscatter at 1 ns intervals and computing the ratio we can determine the fiber's temperature.

Environmental dynamics reflect processes spanning scales from centimeters to kilometers, and this mixture of scales presents profound challenges for description, modeling, and observation. Streams, for instance, grow from water infiltration spread over miles of the headwaters which ushers forth silently from fissures fed by underground aquifers. The water that emerges carries with it the stable temperature of the deep rock, quite distinct from fluctuating surface water temperatures following the daily rhythm of the atmosphere. By observing the temperature of the stream along its whole length with an optical fiber connected to a DTS, it is possible to identify the location and amount of each invisible groundwater contribution (**Figure 1**). This is the stuff of which scientific revolutions are made.

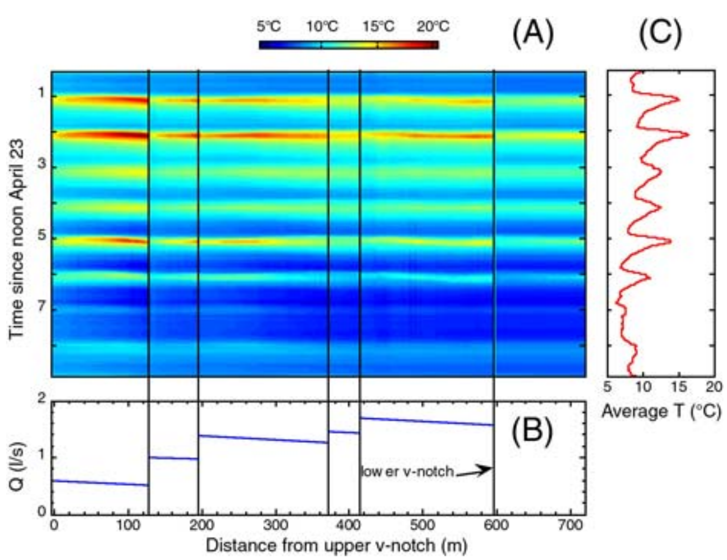

Figure 1. DTS observation of stream temperature in time and space from April 24 to May 3, 2006, for the first 720 m of the Maisbich River in Luxembourg (A). Panel B shows the computed stream flow with groundwater inflows at the dashed lines computed from temperature measurements, and up and downstream flow obtained from weirs. Panel C provides the time-series of spatial averaged temperatures. The first two days (April 24 and 25) were sunny, while the last two days (April 30 and May 1) were cloudy. (from Selker

et al., 2006, with permission).

Environmental applications of DTS are not limited to streams. Consider the following recent examples:

- Lakes—We have observed the internal waves that roll beneath the surface between thermal strata in Lake Tahoe, and we have also observed the exchange of heat between the water and atmosphere in Lake Geneva
- Mines—In the Czech Republic we have observed how contaminated water in abandoned mines mixes and then emerges at the surface from a mile below
- Glaciers—In the Swiss Alps we have documented how the temperature of glaciers reflects their environment;
- Air—In the Cascade mountains of Oregon we have seen how steep valleys pour cold air like invisible rivers
- Snow—In Nevada and Idaho we have measured the patterns of snow accumulation and snow melt

Active Observation

Beyond passive observation, DTS is finding a role in controlled environmental experiments. To understand the proper habitat for trout and salmon, for example, it is critical to explore the processes that control a stream's peak daily temperature. The endangered Chinook salmon, and many other fish, become stressed and die when rising temperatures simultaneously decrease oxygen content of the water, increase the fishes' base metabolism, and increase the reproduction of parasites, leading to catastrophic die-offs when threshold temperatures are crossed. The sun and warm summer air might warm the water, but what might keep it cool? As it turns out, the gravel that forms the channel bed can act as a thermal flywheel, soaking up the peak daily heat as the stream water filters through, and recooling as the nighttime water carries this heat away. The stream you see often represents a small fraction of the total water carried below the surface through the permeable streambed.

To quantify this thermal exchange, we can observe the fate of a cold pulse provided by a sack of ice placed in the river. In reaches where the streambed exchange is large, the cold pulse dissipates almost immediately, as it is soaked up by the temperature-stable gravel. In contrast, in sections where the streambed is lined with bedrock, where water cannot enter and reemerge, the cold signal travels for hundreds of meters. With the help of numerical models, we can translate the meter-by-meter temperature observations we obtain into an equally detailed map of the true depth of the hidden portion of the stream's flow that occurs through the porous gravel beds.

Running a current along the metal casing of the fiber-optic cable allows it to act as a resistive heater. By observing the rate and extent of the resulting temperature change we can actively interrogate the entire length of the cable using DTS. The technique is akin to that used in a hot-wire anemometer to measure wind speed, where the amount of energy removed by the flowing fluid from the device's heated element reflects the flow rate; when the heated fiber-optic cable is placed in the core of a dam, or in a groundwater well, flow is revealed by how much energy the flowing water removes.

In the atmosphere, blimps with fiber-optic tethers can report the fine structure of the atmosphere's temperature, revealing the dynamics of each stratum of the boundary layer. Moreover, using a heated fiber allows us to determine the local wind speeds. Installed below the ground, the fate of a pulse of heat reflects the water content surrounding the fiber, allowing for the simultaneous measurement of soil water content at thousands of locations. If our current plans are realized, NASA and the European Space Agency will use a 54,000 m installation of subsurface, actively heated fiber to calibrate its planned soil-moisture detecting satellite.

Future Aims

It is widely understood that, beyond understanding the natural environment, humanity must consider how to manage the planet. Here again, DTS may play a role. Peak water temperatures are key factors in determining when the nuclear power plants along the Rhine may be operated during the summer. The shutdown of these power plants in the summer of 2003 is thought to have indirectly led to hundreds of deaths because of the lack of air-conditioning. Until now these water temperatures were measured at only a few points but large rivers mix slowly, preventing timely readings. By lacing the bottom of the Rhine with fiber-optic cable, we could measure the river temperatures at many points and thus better determine when thresholds are approached. In the arid west, irrigators have completely shut down water withdrawals to maintain cool stream conditions for fish. If, instead, temperatures were continuously monitored, withdrawals could be managed both to grow food and to assure temperature control of the streams. These are areas of active development.

DTS has revolutionized the measurement of temperature for the oil and process industries and is now opening new opportunities to understand and manage the environment (**Figure 2**). While the applications of DTS are only now being explored, from the results we've seen, even in these formative years, it is clear that DTS will take its place as a workhorse in environmental science.

Figure 2. Laying a fiber-optic cable in the HJ Andrews experimental forest in Oregon in the spring of 2007
