AGU PUBLICATIONS

Water Resources Research

COMMENT

10.1002/2013WR014979

Comment on *Rose et al.* [2013], doi:10.1002/wrcr.20144.

Correspondence to:
J. S. Selker,
John.Selker@Oregonstate.edu

Citation:
Selker, J. S., S. Tyler, and N. van de Giesen (2014), Comment on "Capabilities and limitations of tracing spatial temperature patterns by fiber-optic distributed temperature sensing" by Liliana Rose et al., *Water Resour. Res.*, *50*, 5372–5374, doi:10.1002/2013WR014979.

Received 30 OCT 2013
Accepted 22 APR 2014
Accepted article online 9 MAY 2014
Published online 18 JUN 2014

Comment on "Capabilities and limitations of tracing spatial temperature patterns by fiber-optic distributed temperature sensing" by Liliana Rose et al.

J. S. Selker[1], Scott Tyler[2], and Nick van de Giesen[3]

[1]Department of Biological and Ecological Engineering, Oregon State University, Corvallis, Oregon, USA, [2]Department of Geological Sciences and Engineering, University of Nevada, Reno, Reno, Nevada, USA, [3]Department of Water Resources, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands

Interpreting results from new methods and technology requires understanding of the technical performance of these tools and the underlying physics. Since scientific discovery is often driven by improvements in accuracy, precision, and resolution, understanding these factors is central to realizing these opportunities. An important addition to the suite of tools applicable to environmental observation is fiber-optic distributed temperature sensing (DTS) [e.g., *Selker et al*., 2006a, 2006b]. The recent work of *Rose et al*. [2013] illustrates how essential understanding of performance parameters for new instruments is to avoid confusion over the capabilities and meaning of the output. In the case of DTS, spatial resolution, temporal resolution, accuracy, and repeatability of reported temperatures are intimately related [*Tyler et al*., 2009]. Put into proper context we will show that the work of Rose et al. verified the published instrument specifications of the DTS they employed rather than showing accuracy "critically declining with decreasing signal size" as stated in *Rose et al*. [2013].

In this comment we will focus on spatial sampling and resolution, and follow with a brief discussion of calibration and bias in the reported DTS temperatures. DTS minimum *sample spacing* (an instrument setting) is defined by an instrument as the shortest distance between successive reported temperatures. DTS are typically operated at the minimum sample spacing supported by the instrument manufacturer. DTS reported temperatures are not fully independent for adjacent samples. For this reason, a *spatial resolution* (a performance metric for an instrument) is also specified to indicate how proximal temperature features may actually be distinguished and quantified. *Spatial resolution* is universally larger than the *sample spacing*, sometimes by as much as a factor of 10 (as can be found by reviewing on-line specification sheets for DTS instruments). Instrument performance as specified by its spatial resolution is typically defined as the distance between points reporting 0.1 and 0.9 times, respectively, the true temperature change at a step-wise shift in temperature along a fiber-optic cable. In other words, the distance between points surrounding a sharp temperature change such that the point on the low side is not elevated by more than 10% of the jump and the point on the high side is elevated by at least 90% of the actual jump (see *Tyler et al*. [2009, Figure 3] where they present the same idea but employing 0.05 and 0.95 thresholds, which is more rigorous a standard than employed by convention in the DTS industry when specifying spatial resolution). The key point here is that for some instruments, sample spacing can be chosen to be far shorter than spatial resolution, but that little would be gained by reporting these data. At the same time, for data taken to represent the spatial resolution of the DTS, the Sampling Theorem (often attributed to *Nyquist* [1928]) which states that sample spacing should be no more than half the length of the DTS spatial resolution. Examples of currently available systems have a wide range of performance levels, from 0.125 m sample spacing and 0.29 m resolution (e.g., Silixa Ultima) to 2 m sampling and 4 m resolution (Sensornet Halo, as employed by *Rose et al*. [2013]).

Rose et al. [2013] state "The spatial averaging at [sic] the Halo FO-DTS occurs over 2 m sampling intervals (Sensornet 2009), which is assumed to provide $>$4 m monitoring resolution [*Van de Giesen et al*., 2012]." This statement has two key problems. First, it states that spatial averaging occurs over 2 m, whereas in fact photons are averaged over a distance much longer than this (specifically, the spatial resolution indicates that this is $>$4m). Second, the authors introduce a concept of "monitoring resolution," attributing it to *Van de Giesen et al*. [2012], whereas this concept does not appear in *Van de Giesen et al*. [2012] or any other publication of which we are aware. Though seemingly minor issues, this sets up the work outside of the published definitions of DTS performance [e.g., *Tyler et al*., 2009].

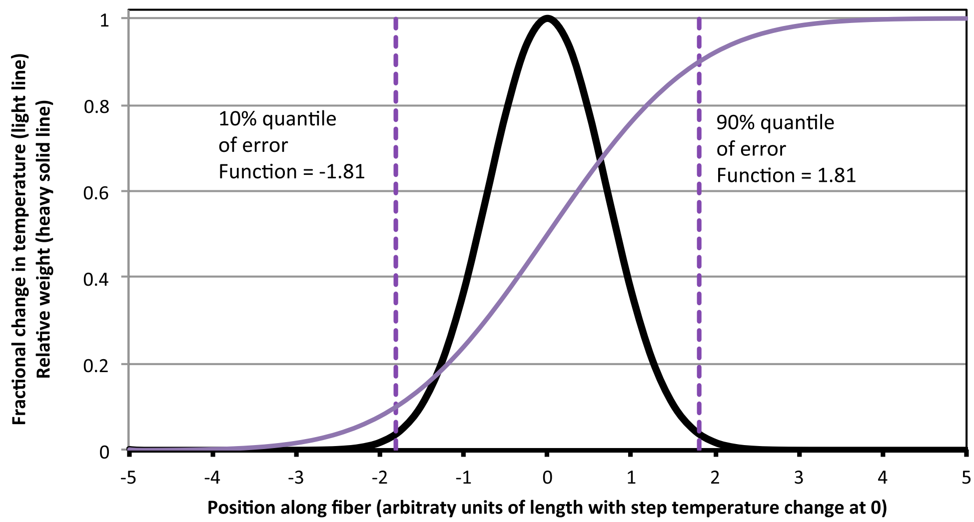

Figure 1. Gaussian curve with maximum of 1 and standard deviation (σ) of 1 illustrating the weighting function implicit in the 10–90 definition of DTS spatial resolution. The thin solid line presents the reported DTS temperatures, the heavy solid line the Gaussian weighting function over which the DTS averages in its reported temperature at position 0, and the dashed lines indicate the locations along the cable of the 10% and 90% quantiles of change in reported temperature where the true change in temperature occurred at position 0 on the horizontal axis.

To interpret the results of *Rose et al*. [2013], it is necessary to understand the spatial weighting of DTS systems. Because of dispersion of light along fiber optics, finite time for lasers to turn on and off, and limitations of optical detectors and their amplifiers to respond to changing signals, reported DTS temperatures are weighted sums of the temperatures along a cable. Our own laboratory tests on several systems have indicated that the weighting function is typically Gaussian (data not shown), which is reasonable considering the nature of these systems. This implies that the reported value for a point x is the weighted sum of the unit Gaussian with standard deviation σ centered at x multiplied by the actual temperatures along the cable. For the remainder of this discussion, we will adopt the assumption that specified spatial resolution is determined by the "10–90" method, which reports the length of fiber required for a DTS signal to travers from 10% to the 90% level of a step change in temperature, and that the true weighting of temperatures is Gaussian (Figure 1). To employ this in practice, we must compute the standard deviation of the Gaussian from an error function fit to the DTS data. The 10%–90% quantiles of an error function occur at -1.81 and $+1.81$ times the standard deviation of the Gaussian. Thus for the Halo $3.62\sigma = 4$ m (the manufacturer's instrument specification), so the standard deviation of the Gaussian weighting function is $\sigma = 1.1$ m.

With this value it is straightforward to estimate the expected reported temperature of a section of cable. Taking the examples from *Rose et al*. [2013, Table 1], for the sampling interval they call "0.25," which is in fact 0.5 m in length, we see that if positioned centrally under the Gaussian weighting function, this would extend 0.25 m/1.1 m $= 0.227\ \sigma$ either side of center of the Gaussian curve. Referring to tables of quantiles for the Gaussian distribution, the $[-0.227, 0.227]$ section of the Gaussian curve represents 0.18 of the total area under the curve. Thus, we would expect the reported temperature for a local step of magnitude ξ to be 0.18ξ. We see that for the cold bath Rose et al. report a value of $(17.8 - 11.21)/17.8 = 0.37\xi$, which is better performance than would have been expected (noting that the ambient temperature of 17.8°C was obtained graphically from Figure 1), and the warm bath $(28.5 - 17.8)/(44 - 17.8) = 0.41\xi$, which is considerably better than would be expected. Considering the "0.5" interval (1 m), this captures 0.35 of the mass of the Gaussian curve, so would be expected to report 0.35ξ. Looking again to *Rose et al*. [2013, Table 1] for the cold bath we find $(17.8 – 9.32)/17.8 = 0.48\xi$, again slightly better than the performance reported by the manufacturer. For the warm bath the values are $(30.78 - 17.8)/(44 - 17.8) = 0.49\xi$, consistent with the cold bath, and in keeping with slightly exceeding the minimum guaranteed performance specifications listed by the manufacturer. Finally, for the "1" interval, the expected performance would be 0.64ξ while the cold bath showed 0.57ξ and the warm bath precisely reproduced this figure with 0.64ξ. Overall we see that the performance reported by *Rose et al*. [2013] was very much in keeping with the manufactures' reported specifications, and the Gaussian weighting expected of DTS behavior.

In addition to these issues regarding resolution, *Rose et al*. [2013] report absolute accuracies (in their terms "divergence from FO-DTS temperatures from thermistor reference measurements") of DTS measurements ranging from less than 1°C to as great as 15.5°C through their test sections, even when the test section length was far greater than the sample spacing of 2 m. Reviewing their Figure 1 indicates that in almost all cases, the reported mean differences between the DTS temperatures and reference thermistor is biased positive in the cold bath case, and very significantly biased negative in the warm bath case. *Rose et al*. [2013] conclude that this bias is solely the result of sample size and as discussed above, is an appropriate conclusion for temperature anomalies that are at or below the instrument spatial resolution.

However, the almost consistent bias even at very large temperature anomalies (7.5 and 25 times the instrument sample resolution) suggest that the reported temperatures are also not well calibrated. *Rose et al*. [2013] state that calibration was conducted on DTS reported temperatures using only the two, 20 m long calibration baths placed at 60–80 and 240–260 m along the fiber-optic cable. Using a simple, two point calibration on DTS temperatures (rather than the raw Stokes and anti-Stokes signals available from the DTS) will produce a less accurate (in absolute terms) calibrated data set than a full three point calibration as suggested by *Hausner et al*. [2011] and will further be compromised if all temperatures reported from the calibration baths are used in a simple two point calibration. When using calibration baths, it is critical that data from well within (spatially) the calibration bath only be used to avoid the exact issues of spatial resolution raised by *Rose et al*. [2013]. Without a detailed reporting of the calibration procedure used, along with careful reporting of the resolution and precision of the reference thermistors used, it is not possible to assess the absolute accuracy of the DTS as claimed by *Rose et al*. [2013]. The presence of a bias at almost all measurement scales implies that any claims of absolute accuracy of the DTS for a given anomaly scale and instrument sampling resolution cannot be justly made.

In general, the physics underlying DTS are very robust and worthy of study for those employing this method. For example, a DTS machine has to assume a certain speed of light of the original pulse and of the Stokes and anti-Stokes wavelengths. Clearly, the exact speeds will depend on the exact make of optical fiber. A small deviation between actual and assumed speeds of less than 1% quickly leads to "dislocations" at distances of hundreds or thousands of meters along the fibers. Further discrepancy between DTS-reported position and the distance along a cable is caused by "overstuffing" of the fiber in the cable wherein the fiber optic is longer than the cable so (typically by on the order of 0.5%) so that if the cable experiences tension and is stretched slightly, the fiber will not experience tension. It is not clear how actual distances were determined in *Rose et al*. [2013]. It is good practice, however, if accurate location is important, to verify measured distances in the field by temporarily heating (or cooling) a small section of the cable. Similarly, it again often pays to work with the measured Stokes and anti-Stokes signals instead of with the temperatures provided by the DTS, since these signals travel at different velocities, and are affected differently by irregularities such a splices or acute bends (broadly referred to as differential attenuation), and thus merit careful evaluation.

It is valuable that *Rose et al*. [2013] took the time to confirm the DTS specifications were valid. We are troubled, however, by Rose et al.'s claiming of "anomalies," "signal loss," "inaccuracies," "dislocations," or that these might lead to "ambiguous interpretations" when reporting data exceeding by up to a factor of eight the reported specifications of the instrument.

References

Hausner, M. B., F. Suárez, K. Glander, N. van de Giesen, J. S. Selker, and S. W. Tyler (2011), Calibrating single-ended fiber-optic Raman spectra distributed temperature sensing data, *Sensors*, *11*, 10,859–10,879, doi:10.3390/s111110859.

Nyquist, H. (1928), Certain topics in telegraph transmission theory, *Trans. AIEE*, *47*, 617–644.

Rose, L., S. Krause, and N. J. Cassidy (2013), Capabilities and limitations of tracing spatial temperature patterns by fiber-optic distributed temperature sensing, *Water Resour. Res.*, *49*, 1741–1745, doi:10.1002/wrcr.20144.

Selker, J. S., L. Thévenaz, H. Huwald, A. Mallet, W. Luxemburg, N. van de Giesen, M. Stejskal, J. Zeman, M. Westhoff, and M. B. Parlange (2006a), Distributed fiber optic temperature sensing for hydrologic systems, *Water Resour. Res.*, *42*, W12202, doi:10.1029/2006WR005326.

Selker, J. S., N. van de Giesen, M. Westhoff, W. Luxemburg, and M. Parlange (2006b), Fiber optics opens window on stream dynamics, *Geophys. Res. Lett.*, *33*, L24401, doi:10.1029/2006GL027979.

Tyler, S. W., J. S. Selker, M. B. Hausner, C. E. Hatch, T. Torgersen, C. E. Thodal, and G. Schladow (2009), Environmental temperature sensing using Raman spectra DTS fiber-optic methods, *Water Resour. Res.*, *45*, W00D23, doi:10.1029/2008WR007052.

Van de Giesen, N., S. C. Steele-Dunne, J. Jansen, O. Hoes, M. B. Hausner, S. Tyler, and J. S. Selker (2012), Double-ended calibration of fiber-optic Raman spectra distributed temperature sensing data, *Sensors*, *12*(5), 5471–5485, doi:10.3390/s120505471.

