Capabilities and challenges of distributed Brillouin sensing in geotechnical applications

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ABSTRACT: Distributed fiber-optic strain and temperature measurement on the base of spatially resolved Brillouin sensing have developed to a widely accepted monitoring tool in a variety of applications for the structural health assessment in concrete, soil and surface applications. In many of such applications, distributed sensing can be employed to directly replace conventional sensors; in other applications, such a one-to-one replacement is not so easy, which largely depends on the specific physical quantity as well as the structure's geometry of the desired measurement scheme.

This paper addresses the specific nature of distributed strain sensing data as provided by Brillouin measurements in optical fibers. It highlights the sometime confusing definitions of spatial resolution, spatial accuracy and measurand repeatability and outlines their interdependency when configuring distributed measurements. Finally, an industry example on the correlation of distributed strain data with conventional sensors is given, covering sensor integration into concrete piles.

1 INTRODUCTION

In many industrial monitoring applications, distributed Brillouin sensing has been successfully implemented as a one-to-one replacement of classical point sensors. Especially in monitoring tasks where electrical strain gauges or extensometers have been used to cover the requirements on structural health monitoring in a conservative approach, the geometrical orientation of the physical measurand (which is the structure's length change, in parallel to the sensor's orientation) allows its adequate capture by measuring the sensing fiber's longitudinal strain.

In other applications, such a direct replacement is not possible, because the true nature of the measured quantity (such as geometrical displacement or transient mechanical deformation) might not be directly transferrable into longitudinal strain, which is actually the quantity that is measured by distributed Brillouin sensing.

Moreover, the nature of truly distributed data – a series of data points that represent the equally spaced positions along the sensing fiber (Figure 1) – often leads to difficulties in assessing how exactly a series of discrete, independent point sensors can be replaced.

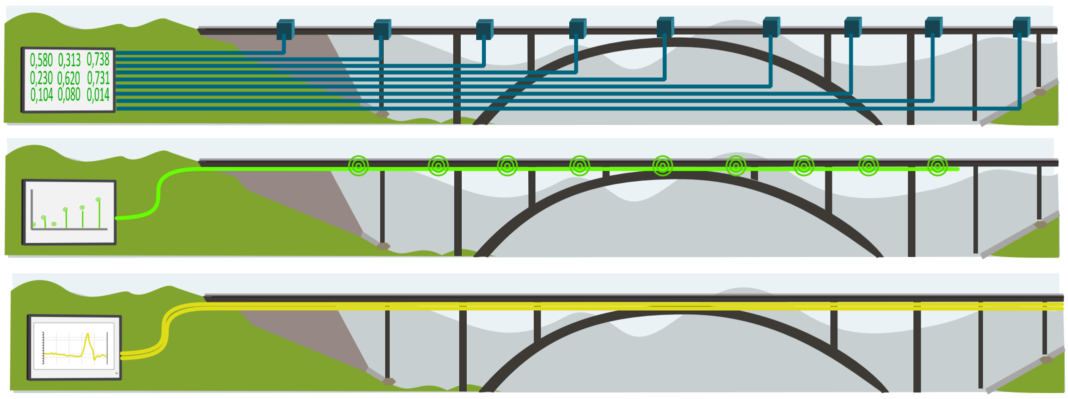


Figure 1. Schematic depiction of the definitions of discrete (*top*), quasi-distributed (*center*) and distributed (*bottom*) sensing points.

It has been found in the authors' practical experience in industrial applications, that it is mainly the following aspects of the nature of distributed strain sensing data that imply obstacles in the application of the technology where so far discrete or quasi-distributed technologies had been applied:

- Distributed data instead of discrete independent points: Each data point of a distributed system represents the integrated strain over the length of the distance to the following data point. Moreover, the data points are virtually lined up along the sensing fiber; their position is not physically linked to the geometry of the structure. In contrast, classical point sensors like strain gauges are fixed to a structure and will deliver the strain quantity of their gauge length, with no impact from any other adjacent sensor read-out throughout the structure.
- Orientation of the geometrical component of the measured strain: Depending on the expected orientation of the main geometrical component of a displacement to be monitored, discrete and quasi-distributed sensing points are often aligned in a way that this main component meets the orientation of the sensor. In contrast, a distributed fiber-optic sensor is usually deployed in an orientation that corresponds to the general orientation of the overall structure (along a tunnel, an embankment etc.). Consequently, measuring the longitudinal component of a deformation that is in orthogonal direction to this orientation, a significant diminishment of the measured quantity must be accounted for (see Figure 2).

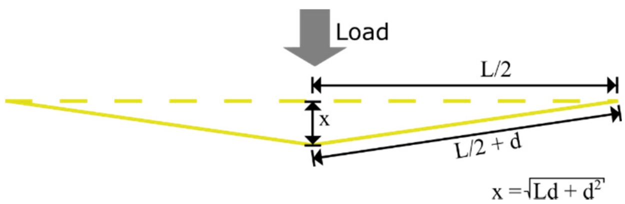


Figure 2. Measured strain based on the length change d of a distributed longitudinal sensor over a segment of length L due to a orthogonal load resulting in a displacement x

In order to further discuss such challenges of the deployment of distributed sensors and yet to fully exploit the main benefits and advantages over discrete sensors, their specific characteristics are further discussed in the following.

2 PERFORMANCE SPECIFICATION PARAMETERS OF DISTRIBUTED SENSING

With the increasing number of industrial applications for distributed fiber-optic strain and temperature sensing technologies, there is a growing demand for comparable performance data of the sensing instruments. A comprehensive set of clear definitions for the resolution and accuracy characteristics – taking the unconventional nature of distributed sensing data into account – shall help industrial and academic users to evaluate the technology and introduce its benefits into new applications.

2.1.1 Spatial resolution and spatial accuracy

For truly distributed fiber-optic sensing systems such as Raman DTS or Brillouin DTSS, the spatial resolution is one of the central performance figures: when comparing different technologies or manufacturers, this number is of high importance.

However, when looking at spec sheets or user interfaces of different Brillouin DTSS systems, the user will not only find a "spatial resolution" figure, but also terms like "spatial accuracy", "distance resolution" and "distance sampling rate" .

In the following, the different terms and their implication for a system's measurement performance are explained in detail.

- **Spatial resolution:** For the reliable detection of physical strain and temperature events, the spatial resolution – following the definition that is widely agreed on – is the most important figure (Thevenaz, L., Habel, W.R. (2007)):

  The spatial resolution is specified for a fiber by the minimum distance between two step transitions of the fiber's strain / temperature condition. It is directly related to the pulse length of the measuring instrument.

- **Spatial accuracy:** This is the distance between two measurement points in the resulting measurement curve of the strain / temperature profile along the fiber. As this can be increased by changing the sampling rate of the instrument's digitizer, or by post-processing operations like interpolation schemes, a higher number of data points within the length of the optical pulse do not provide independent strain or temperature readings. They do, however, increase the accuracy of the spatial reallocation of physical events (like the edge of a strain transition) in the measurement curve.

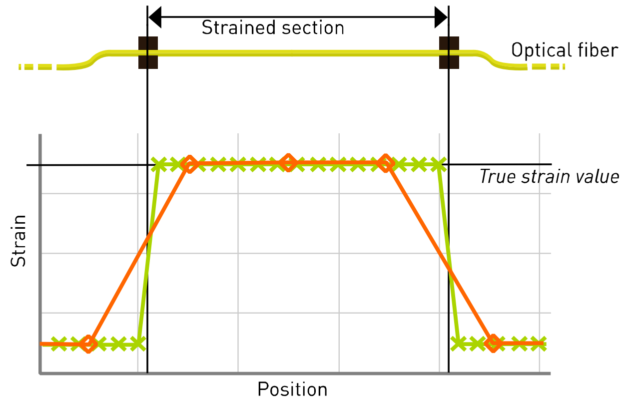
The following figures illustrate these definitions for step transitions of a fiber's strain condition.

Case 1:
Length of the strained section is three times the spatial resolution.

The strain of the fiber is measured correctly; a higher spatial accuracy provides more precise reallocation of the position of the steps.

Spatial accuracy = spatial resolution

Spatial accuracy = 5x spatial resolution

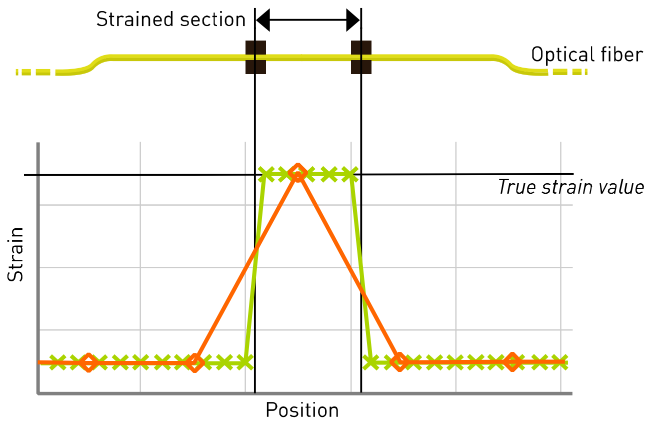


Case 2:
Length of the strained section is equal to the spatial resolution.

The strain of the fiber is measured correctly; a higher spatial accuracy provides more precise reallocation of the position of the steps.

Spatial accuracy = spatial resolution

Spatial accuracy = 5x spatial resolution



Case 3:
Length of the strained section is half as long as the spatial resolution.

The strain of the fiber is not measured correctly; a higher spatial accuracy does not increase the reliability of measuring short physical events.

Spatial accuracy = spatial resolution

Spatial accuracy = 5x spatial resolution

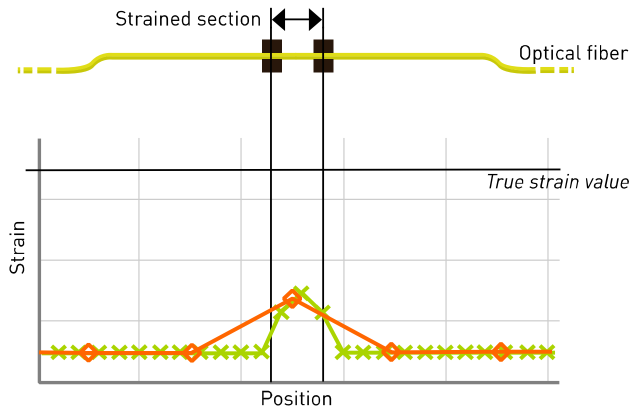


Figure 3. Definitions of spatial resolution and spatial accuracy for distributed strain sensing data in the case of a step-transition strain event

2.1.2 Strain and temperature repeatability, precision and accuracy

The terms "accuracy", "repeatability", "reproducibility", "cross-sensitivity" and "sensor calibration" are often used in a non-consequent and non-consistent manner when it comes to the practical implications of distributed sensor technologies. Such terms need to be handled with respect to the substantial differences between distributed sensing technologies and point-wise or quasi-distributed sensing technologies, but also to the differences among different distributed sensing principles (Brillouin DTSS, Raman DTS, Rayleigh OTDR / OBR etc.).

From Thevenaz, L., Habel, W.R. (2007), we see:

Accuracy: It qualitatively expresses the closeness of the measured value to the true or ideal ('master') value of the measurand. Accuracy represents the difference between the measured result and the true value and is affected by both bias and precision.

Precision: It describes how repeatable a measurement result is. Precision is expressed by the estimated standard deviation of a specified series of measurements. (Sometimes precision is expressed as a multiple of the estimated standard deviation, e. g. 2σ). The smaller the dispersion of the measured values, the better the precision; precise measurement results need not to be necessarily accurate (e.g. due to bias). Therefore a result of a single measurement should be interpreted as drawn from an ensemble with the measured standard deviation.

Specifically, for distributed Brillouin sensing, these definitions need to be further investigated. Distributed Brillouin sensing gets the information on fiber temperature and strain from the Brillouin frequency shift, which is an intrinsic property of the optical sensing fibers. Each position along the fiber at a given strain/temperature condition corresponds to a Brillouin shift value in the instrument's output data.

Two linear coefficients provide the connection between the measured Brillouin frequency shift and the desired values of strain and temperature. These coefficients need to be determined for each type of sensing fiber or cable.

The instrument's precision is the repeatability when measuring the Brillouin frequency shift in identical conditions over a series of measurements. This repeatability is expressed in twice the standard deviation (2σ) of the Brillouin shift values at every location.

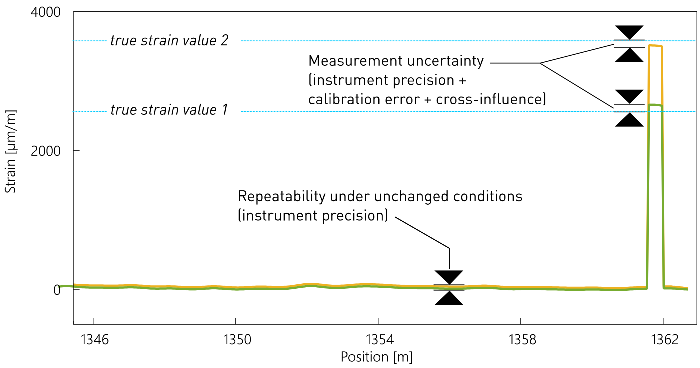


Figure 4. Distributed measurement data illustrating the definitions of uncertainty, accuracy, precision and repeatability

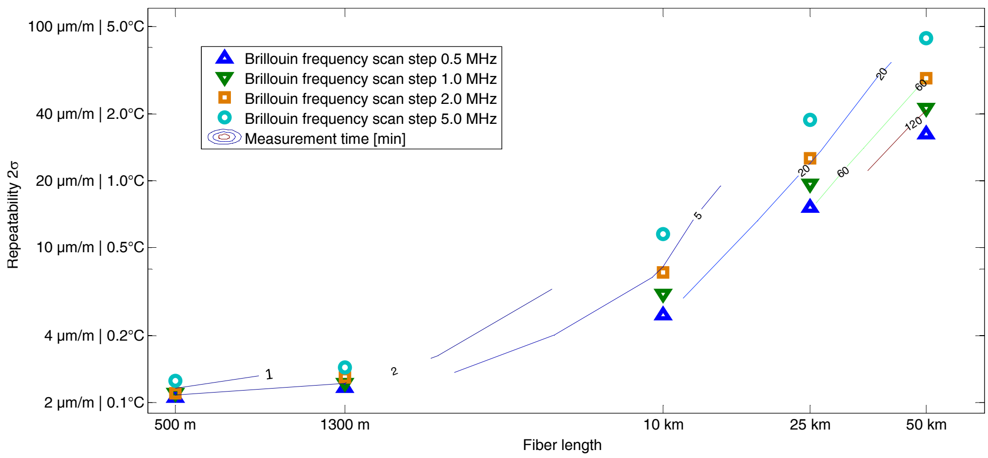
Under the assumption of error-free calibration and an ideal decoupling of strain and temperature, the uncertainty of strain and temperature corresponds to the repeatability of the Brillouin frequency shift.

In practice, it has been found a reliable measure of the system's precision to perform 10 successive measurements under stable, controlled conditions regarding temperature and strain, then to calculate the 2σ figure for each data point and take the average of this value for the 10% of sensor length furthest away from position $z = 0\ m$ (where the noise performance generally is lower).

3 INTERDEPENDENCY OF THE PARAMETERS

A distributed sensing system has to be configured with respect to the user's specifications on spatial resolution, accuracy and sensing fiber length. In most cases, this latter parameter is governed by the installation itself; in other applications, the measurement time will govern all other parameters, and finally, the installation quality (avoiding small bending radii along the installation, careful optical splices and clean connectors, etc.) will impact on this interdependency by introducing the optical attenuation as a major impact on the measurement quality.

For the practical assessment of this scheme, true measurement data is given in the following figures for a variety of fiber length, investigating various values for spatial resolution as well as for the frequency step of the Brillouin shift scan. The assessment of the repeatability figure follows the procedure outlined in section 2.1.2.



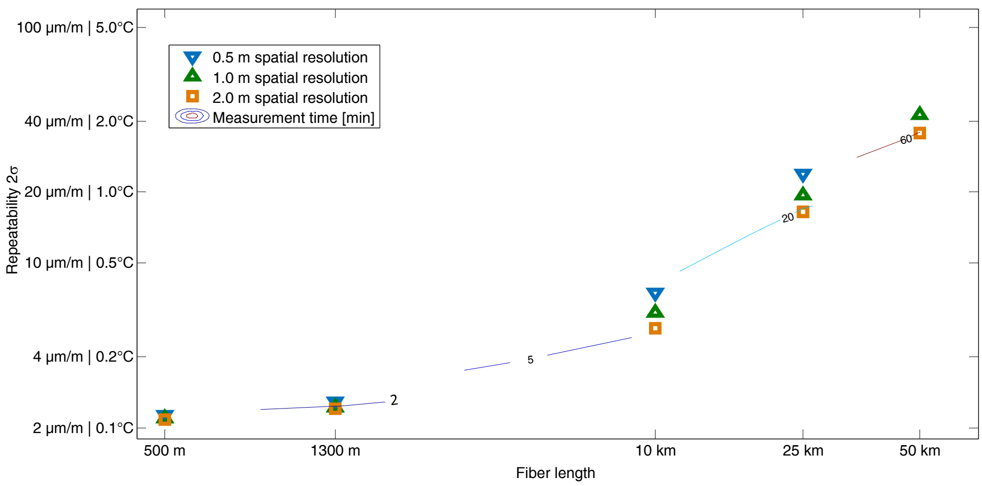


Figure 5: Repeatability and measurement times for a fixed spatial resolution of 1 m (*top*) and for a fixed Brillouin frequency scanning step of 1 MHz (*bottom*)

4 INDUSTRIAL EXAMPLE: STATIC PILE LOAD TESTING

Static load measurements for concrete piles using extensometers and parallel distributed optical strain sensor cables with Brillouin measurements were performed. Such measurements, using Brillouin systems for static load testing of concrete piles, have been reported for various sensing configurations (Kecharvazi, C., Soga, S. et.al., 2016).

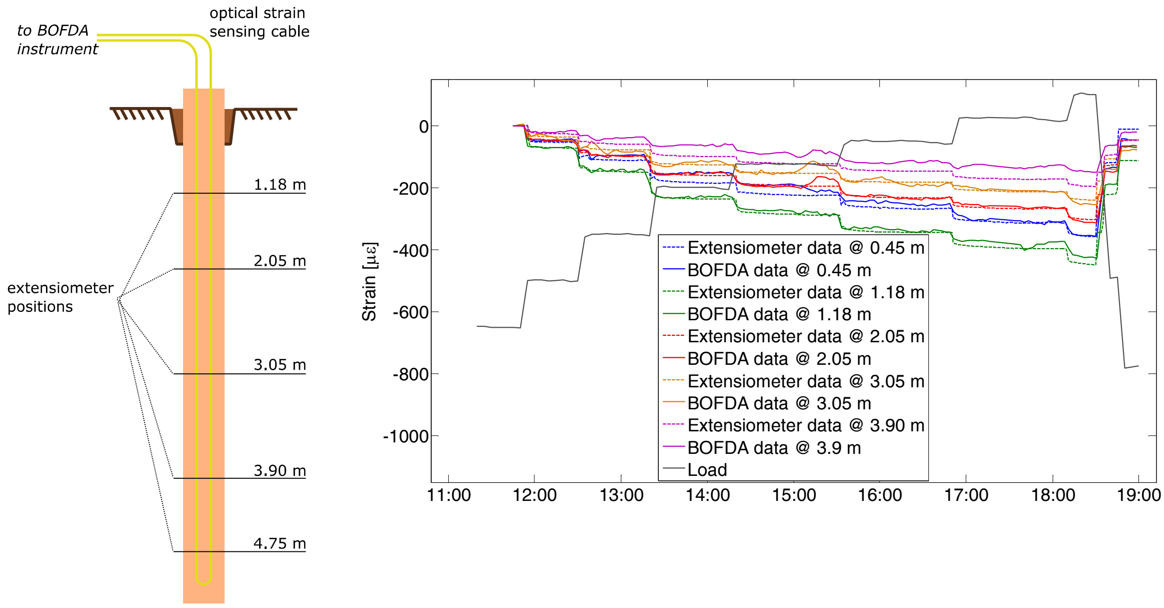


Figure 6: Set-up (*left*); Evolution of strain for both the extensometers and the distributed Brillouin sensors (at the exact extensometer positions, compensated for the base line reading at 0 kN load) over time (*right*).

The application comprises a concrete-poured pile of 5 m depth; reinforced, steel-armored fiber-optic sensing cables were fixed to the reinforcement cage before entering the cage into the ground.

During the tests, an increasing vertical load from 150 kN to 900 kN was induced onto the pile, while subsequently extensometer data as point-wise references, temperature data at the extensometer positions and distributed Brillouin strain data were recorded.

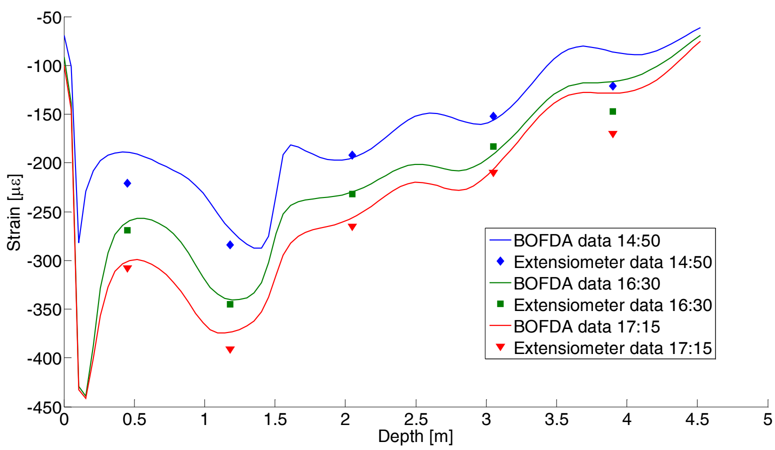


Figure 7: Spatial evolution of strain at 3 selected points in time

With the exemption of the lowest extensometer, all the measurement points show good agreement between the classical data and the fiber-optic sensing data.

5 CONCLUSIONS

From the point of view of an end user of Brillouin DTSS systems, the definitions of spatial resolution, spatial accuracy and measurand accuracy / precision are often not sufficient to reliably characterize system performance in direct instrument comparisons. This field of lacking definitions has been outlined with examples from lab measurements and pile testing field data.

6 REFERENCES

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