Distributed Brillouin Sensing for Geotechnical Infrastructure: Capabilities and Challenges

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ABSTRACT: Distributed Brillouin sensing has become a state-of-the-art tool for strain and temperature monitoring in concrete and geotechnical applications throughout the civil construction industry. While commercially available systems are steadily advancing in terms of spatial resolution and measurement length, end-users in field installations often put the focus on softer parameters like linearity or optical budget when evaluating the performance of the technology.

This paper addresses the implications of high spatial resolution to the accuracy of relative and absolute strain and temperature data from the perspective of the Brillouin optical frequency domain analysis (BOFDA) technology, and outlines the need for a clear definition and a standardization scheme to make the terms dynamic range and optical budget comparable between different instruments and technologies. Data from field applications in concrete pile monitoring is used to discuss the above aspects.

KEYWORDS: Distributed fiber-optic Brillouin sensing, BOFDA, Spatial resolution, Dynamic range

1. INTRODUCTION

For long-range measurements in geotechnical and industrial applications, distributed temperature and sensing (DTSS or DSTS), also referred to as distributed Brillouin sensing, has become a widely accepted monitoring tool in a variety of applications for the structural health assessment in concrete, soil and surface applications. The advantageous nature of truly distributed measurements becomes apparent from the perspective of conventional measuring methods: Classic deformation monitoring (performed by strain gauges etc.) and temperature monitoring (Pt100 and alike) deliver data from fixed, single spots of a structure; quasi-distributed measurements (fiber Bragg gratings) provide a chain of discrete measurement points.

In contrast, an optical fiber connected to a device for distributed strain and temperature sensing will provide a continuous profile of strain and temperature – spatially resolved down to less than 0.5 m – over a range of several tens of kilometers.

However, a one-to-one replacement of conventional discrete sensors, as an end-user or system integrator oftentimes might wish for, will have to take several specific aspects of the distributed nature of DTSS into account. For one, there is the geometrical orientation of the physical measurand (e.g., the structure's length change, in parallel to the sensor's orientation) – and whether it is adequately captured by measuring an optical fiber's longitudinal strain (Figure 1 illustrates this challenge).

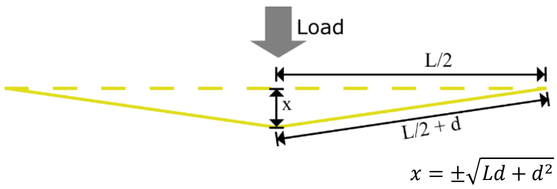


Figure 1 Measured strain based on the length change *d* of a distributed sensor over a segment of length *L* due to an orthogonal displacement *x*. The challenge: *d* will be considerably smaller than *x*

Moreover, a system's characterization parameters, such as accuracy, precision, resolution (both space and measurand) and dynamic range also need to be handled with care when comparing discrete and distributed systems. This paper will outline the above parameters in their common definitions and specific meaning for distributed sensing and address the need for further industry-wide discussions on a common understanding.

2. PERFORMANCE SPECIFICATION PARAMETERS OF DISTRIBUTED SENSING

When comparing and classifying sensing systems with respect to real-life application requirements, a straight-forward approach is to apply performance parameters known from classical point-wise sensors to distributed sensing systems – such as precision, gauge-length, long-term stability etc.

However, the continuous nature of data resulting from distributed sensing systems requires a set of performance parameters that are fundamentally distinct from those characterizing classical point-wise sensors; and even among the different distributed technologies, different parameters or interpretations of such parameters will apply.

As an example, the precision and accuracy figures of distributed temperature measurements will fundamentally differ when comparing data recorded by Raman DTS systems to data recorded by Brillouin DTSS systems: Raman DTS employs the backscattering intensity (i.e., the intensity ratio between the Stokes and Anti-Stokes component of Raman-backscattered light), thereby providing absolute temperature data; the end-user will be interested in long-term effects altering this intensity distribution, there-by degrading precision in the long term.

In contrast, Brillouin DTSS data relies on a frequency information that is inherent to the physics of the fiber; once calibrated, the temperature response will remain stable; thus, the accuracy figure of the system becomes equal to the repeatability of the da-ta. This inherent stability in turn puts high demand on the calibration of the Brillouin coefficients (connecting the Brillouin frequency reading to strain and temperature) and to separate mechanical strain from temperature impacts on the sensor (or, in this example of pure temperature readings, to provide strain-free implementation of the sensing fiber into the structure).

2.1 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.

  The first part of the definition provides a clear criteria to determine a system's spatial resolution (e.g. by fixing a fiber section on a linear strain stage). However, the second part (the relation to the pulse width) gives physical background that bears the danger of making an invalid reversal conclusion:

  In linear time domain backscattering reflectometry (e.g. OTDR), the spatial resolution δz is connected to the optical pulse width by

  $$\delta z = \frac{1}{2}\frac{c_0}{n}\Delta t_p$$

  in which c_0 is the vacuum speed of light, n is the refractive group index of the fiber and Δt_p is the width of a presumed rectangular pulse.

  This relation also applies to distributed Brillouin sensing systems and thereby makes the above definition of spatial resolution generally valid. However, the physics of Brillouin backscattering introduce limitations into this relation: A pulse width significantly shorter than 10 ns will introduce an uncertainty into the measurement value and degrade both spatial and strain/temperature precision (Thevenaz and Beugnot, 2009).

  Therefore, characterizing an instrument's spatial resolution by merely providing the pulse width will not hold true under all circumstances; other impacts like fiber losses might also prevent the system from detecting a small event even though the nominal pulse width should theoretically allow the detection.

  In consequence, this issue can be seen as an ex-ample of parameter definitions that originated from other technologies or the physical background of the technology, but need an application-oriented revision with respect to what end users expect from data sheets and instrument comparisons. It stresses the obvious need for standardized parameter definitions as it has been done in the work of Iten, Spera, Jeyapalan et al. 2015.

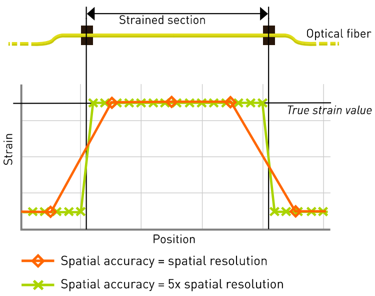
- Spatial accuracy: This is the distance between two measurement points in the resulting measurement curve of the strain / temperature profile along the fiber. As this can be increased by changing the sampling rate of the instrument's digitizer, or by post-processing operations like interpolation schemes, 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 set of figures (Figure 2) illustrates these definitions for step transitions of a fiber's strain condition.

Case 1:

Length of the strained section is three times the spatial resolution.

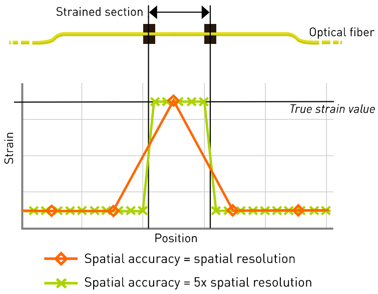
The strain of the fiber is measured correctly; a higher spatial accuracy provides more precise reallocation of the position of the steps.



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.



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.

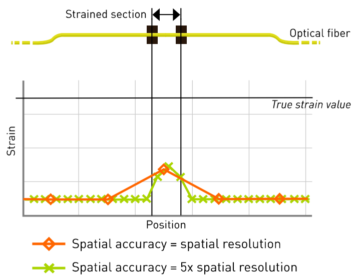


Figure 2 Definitions of spatial resolution and spatial accuracy for distributed strain data in the case of a step-transition strain event

2.2 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 corresponds to a Brillouin shift value in the instrument's output.

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 (see Figure 3 for an illustration of this).

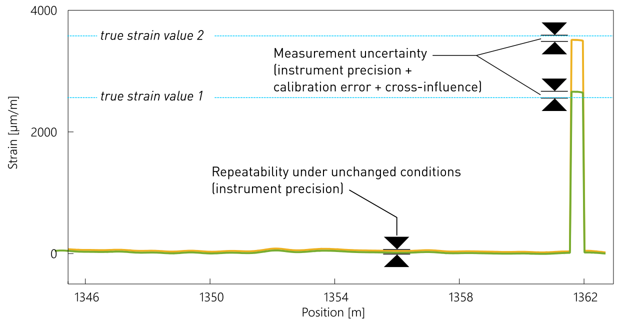


Figure 3 Distributed measurement data illustrating the definitions of uncertainty, accuracy, precision and repeatability

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).

When it comes to in-practice monitoring tasks that aim at the measurement of changes in temperature or strain relative to a baseline measurement, the measurement repeatability governs the measurement quality. Absolute uncertainty impacts such as cross-influences or calibration offsets will not affect this relative accuracy. An imperfect calibration coefficient, however, will not be part of the repeatability evaluation, but still impact relative measurements.

2.3 Dynamic range and loss budget

Another parameter characterizing a distributed sensing system is the systems dynamic range. Similar to the spatial resolution, the definition has been established for OTDR instruments. Figure 4 shows the definition (specified by IEC 61746):

Here, the dynamic range is defined as the difference (in a logarithmic backscattering graph) between the full scale level of the receiver and the upper limit of a range that contains at least 98% of all noise da-ta points.

This definition allows the user of an OTDR to answer the central question: Will this instrument be able to detect a significant event even after a fiber section that induces optical losses of x dB?

Conclusively, an OTDR's dynamic range corresponds to its loss budget or attenuation budget – the maximum fiber attenuation to still allow quantitative distributed measurements.

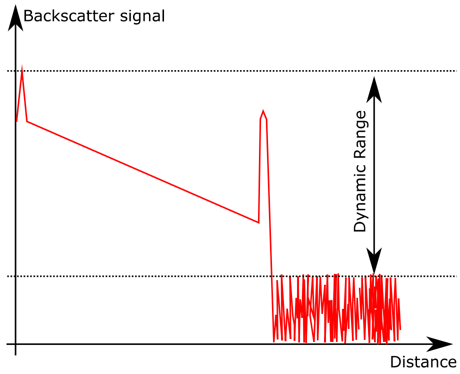


Figure 4 OTDR definition of dynamic range

For Brillouin DTSS systems, it is of course a straight-forward approach to adopt this exact definition, because it takes the components' specifications into account (laser power, detector's sensitivity) and provides a clear number that the end user might be used to. However, the system's dynamic range as de-fined for OTDR is not necessarily equivalent to the system's loss budget. Figure 5 explains why the loss budget is a far more complex figure for Brillouin DTSS systems than for OTDR.

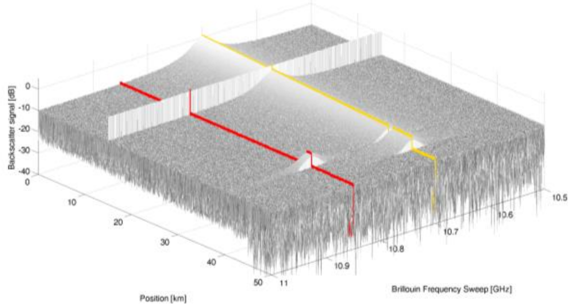


Figure 5 Distributed profile of Brillouin gain from an optical fiber (simulated, as it would be recorded by a Brillouin DTSS system)

The graph shows a homogenously strained fiber of 40 km length; towards the fiber end, there is a strained section where the maximum Brillouin gain is shifted towards higher frequencies, and at ca. 10 km, there is a strong Fresnel reflection (e.g., a bad connector).

Brillouin gain decreases with fiber length and attenuation; at the fiber end, there is still a significant step down to the noise floor. Yet, for the detection of the strain section, this step is obviously not the only relevant criteria. This becomes clearer when looking at the two cross sections as they are indicated in Figure 5, see Figure 6.

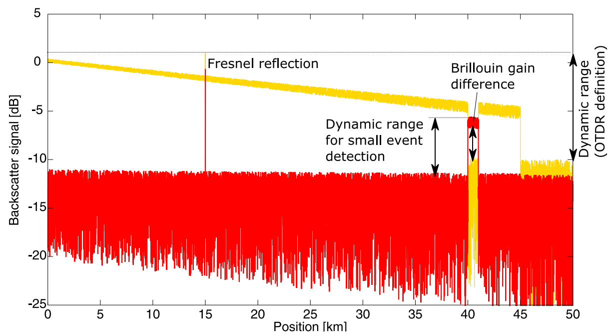


Figure 6 Cross-section at the marked positions in Figure 5

The basic OTDR definition from Figure 4 still applies to characterize the system's performance in detecting high and low backscattering and reflection levels. The performance when clearly detecting small strain or temperature events, however, must take more parameters into account; especially, because the level of Brillouin backscattering received per section also depends on the overall length of fiber that has this exact Brillouin frequency shift. This origins from the non-linear nature of Brillouin scattering and is indicated by the lower level of backscattering at pos. 40 km in Figure 6 compared to the level of the homogenous fiber.

At this point, the loss or attenuation budget of a Brillouin DTSS system will substantially differ from its dynamic range and become an empirical parameter which is not meaningfully expressed by just adding up the components' sensitivity characteristics.

In consequence, our proposal is not to use the dynamic range figure as a parameter in Brillouin DTSS, but rather to define a meaningful set-up – such as a homogenous fiber, only strained at one defined position over a length in the range of the system's spatial resolution – in order to benchmark the system's ability to correctly resolve this event. With increasing optical attenuation in this set-up, the system's optical budget can be achieved.

Figure 7 and Figure 8 show a section of a homogenous fiber of 475 m length, of which 0.5 m (at pos. 453.5 m) have been strained in a linear stage.

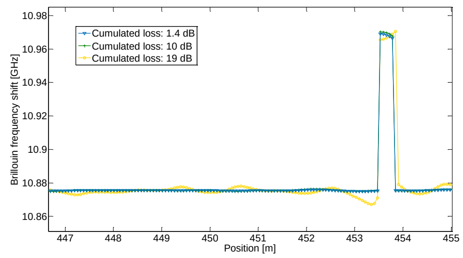


Figure 7 Brillouin DTSS trace of a 0.5 m strained fiber section

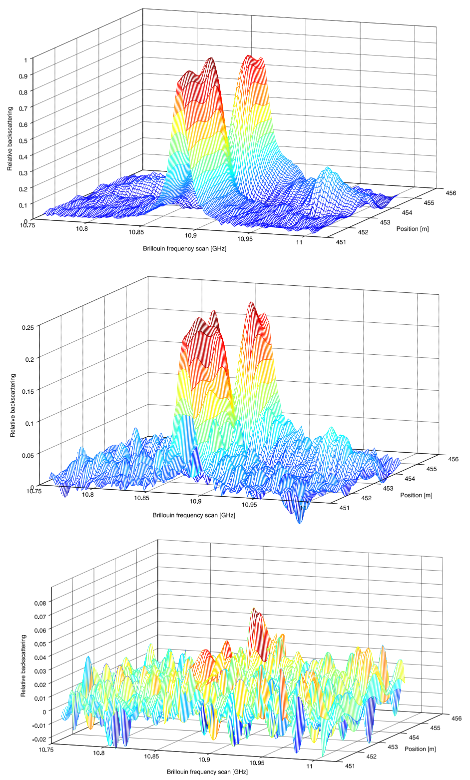


Figure 8 Raw Brillouin data of the measurement traces shown in Figure 7 (Top: 1.4 dB; center: 10 dB; bottom: 19 dB cumulated loss). An unambiguous trace has still be deducted (Figure 7).

2.4 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.

Figure 9 proposes a scheme to explain the interdependency of the mentioned key performance figures.

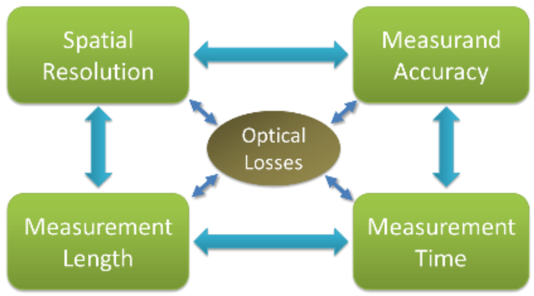


Figure 9 Interdependency of the performance parameters of distributed fiber-optic sensing systems

For the practical assessment of this scheme, true measurement data is given in the following Figure 10 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 2.2.

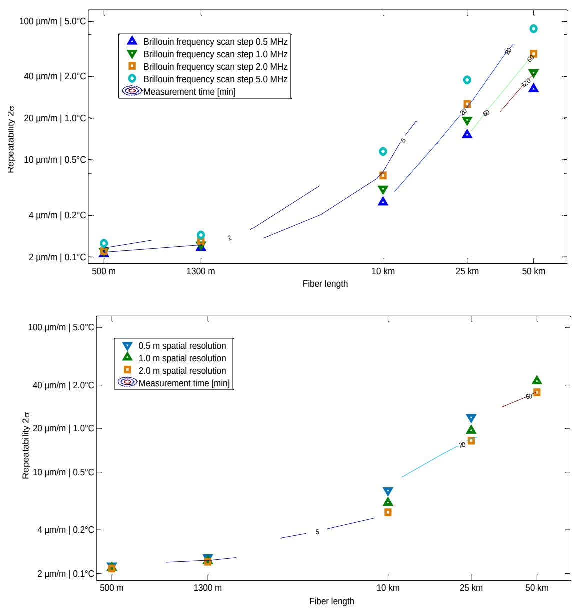


Figure 10 Repeatability and measurement times for a fixed spatial resolution of 1 m (top) and for a fixed Brillouin frequency scanning step of 1 MHz (bottom). The annotated line contours represent the measurement time in minutes

3. PILE TESTING USING DISTRIBUTED BRILLOUIN SENSING

In order to provide an example of how different a spatially resolved strain measurement in the lab (as the one shown in Figure 6) can be from a distributed strain measurement performed within an industrial application, data from a static pile load testing campaign is shown.

Static load measurements for concrete piles using extensometers and parallel distributed optical strain sensor cables with Brillouin DTSS measurements were performed as sketched in Figure 11.

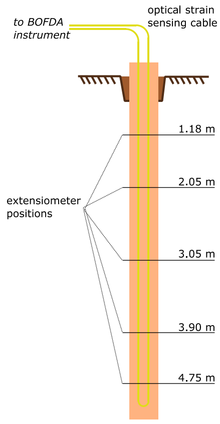


Figure 11 Measurement set-up for static pile load testing

Such measurements, using Brillouin DTSS systems for static load testing of concrete piles, have been re-ported for various sensing configurations (Schwamb, Elshafie, and Ouyang 2011).

The present 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 pouring and curing of the concrete, the sensing cables were not damaged, so the overall optical loss remained within the limits of a few dB.

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 12 shows the evolution of strain for both the extensometers and the distributed Brillouin sensors (at the extensometer positions, compensated for the base line reading at 0 kN load) over time.

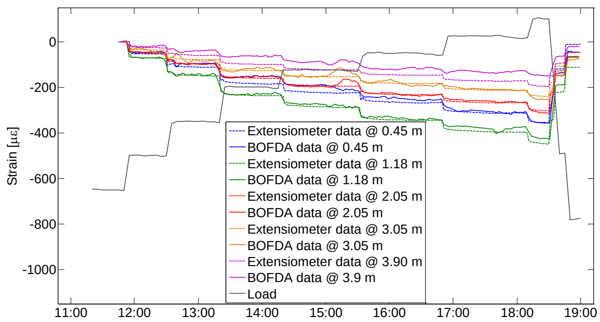


Figure 12 Strain evolution: Extensometer and Brillouin DTSS data

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

Naturally, in such a representation, the distributed nature of Brillouin DTSS is not accounted for. Figure 13 therefore shows the spatial evolution of strain at 3 selected points in time, again in good agreement to the extensometer data. Such distributed data show the true benefit of DTSS measurements: Spatially continuous strain values instead of point-wise data with no information between the measurement points. For the full picture, Figure 14 combines the perspectives from Figures 13 and 14

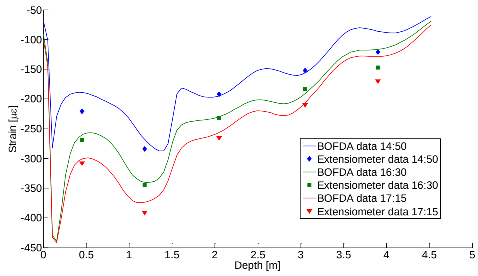


Figure 13 Spatial strain in extensometer and Brillouin DTSS data

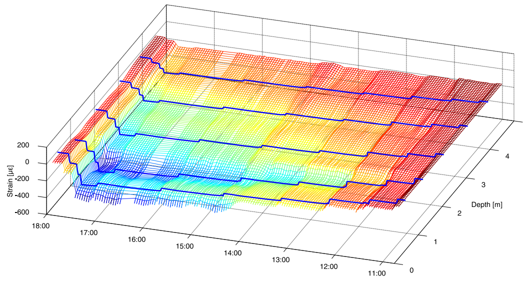


Figure 14 Spatial and temporal strain evolution in extensometer and Brillouin DTSS data

4. CONCLUSION

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

5. ACKNOWLEDGEMENT

We would like to thank Ryszard Rippel from Piletest Rippel for a fruitful collaboration on the presented studies. Note on the Brillouin DTSS measurements: All measurements shown herein were performed using fibrisTerre's fTB 2505 system that employs the Brillouin optical frequency domain analysis (BOFDA) technology.

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