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Leakage detection using fiber optics distributed temperature monitoring

Marc Nikles[a], Bernhard Vogel[b], Fabien Briffod[a], Stephan Grosswig[b], Florian Sauser[a], Steffen Luebbecke[b], André Bals[a], Thomas Pfeiffer[b]

[a] Omnisens SA, PSE-C, CH-1015 Lausanne, Switzerland
[b] GESO GmbH Jena, Loebstedter Str.47b, D-07747 Jena, Germany

Abstract:

The monitoring of temperature profiles over long distance by means of optical fibers represents a highly efficient way to perform leakage detection along pipelines, in dams, dykes, or tanks… Different techniques have been developed taking advantages of the fiber geometry and of optical time domain analysis for the localization of the information. Among fiber optics distributed temperature sensing techniques, Brillouin-based systems have demonstrated to have the best potential for applications over distances up to several tens of kilometers. The key features and performances are reviewed in the present article and a 55km pipeline equipped with a fiber optics leakage detection system is presented as a case study.

Keywords: *pipeline monitoring, leakage detection, distributed strain and temperature monitoring, Brillouin scattering, fiber optics sensor.*

1. Introduction

Leakages of oil and gas from pipeline are dangerous for people and the environment: oil contaminates soil and groundwater, whereas gas leaks can cause explosions and are harmful to vegetation and atmosphere. Furthermore oil and gas leakages may introduce high economic losses. However, detection of leakage along pipelines which is obviously an important part of the maintenance activity has always been a difficult task. Most of the time, a visual inspection of the pipeline is required to attest of the absence of leakage. In the case of buried pipeline, where an inspection is not possible, the presence of a leak is identified by a drop of the pressure. Moreover, pressure tests are periodically performed to check the integrity of the pipeline even though the reliability of the test is relatively poor due to the influence of temperature differences along the pipeline. As a result pipeline operators have been looking at new solutions for the detection of leakage through the monitoring of the pipeline surrounding temperature.

In the past few years, innovative distributed temperature monitoring techniques using optical fibers have demonstrated to be an efficient way to detect and localize leakages along pipelines [1]. These techniques use a concept similar to Optical Domain Reflectometry (OTDR) for the localization, whereas the temperature information is extracted from the analysis of the scattered light through Raman or Brillouin scattering processes. Raman-based systems were first proposed [2] and used in practical applications, while the Brillouin-based technique has been introduced in the early nineties [3, 4] and offers longer distance ranges [5, 6].

The present paper presents and discusses the possibility to actively and automatically monitor leakages using distributed fiber optics sensing techniques. The second part of the paper focuses on a practical case study – a 55km brine pipeline which is equipped with a complete leakage detection system based on a fiber optics Brillouin distributed temperature measurement system.

2. Leakage detection using fiber optics distributed temperature monitoring

Leakages from pipeline introduce local temperature anomalies in the vicinity of the pipeline. Depending on the type of substance transported through the pipeline, it may be either a local warming (crude oil, brine, heating systems) or cooling (gas pipeline). For optimized transport of oil through pipelines, the oil is warmed up and in the case of leakage the surrounding soil temperature increases accordingly. On the other hand, leakages from pressurized gas pipelines introduces a temperature cooling due to gas expansion and the associated temperature drop, the so-called Joule-Thomson effect. As a result, monitoring the surrounding pipeline temperature appears to be an efficient way to detect leakages.

Contact : marc.nikles@omnisens.ch; Phone : +41 21 693.84.87 ; www.omnisens.com

The threadlike geometry of optical fibers and their low propagation loss characteristics make them excellent candidates for the monitoring of pipeline over long distances (up to several tens of kilometers). Furthermore, recent fiber optics distributed sensing techniques have offered innovative solutions for temperature monitoring, providing an uninterrupted measurement of the fiber temperature as a function of distance.

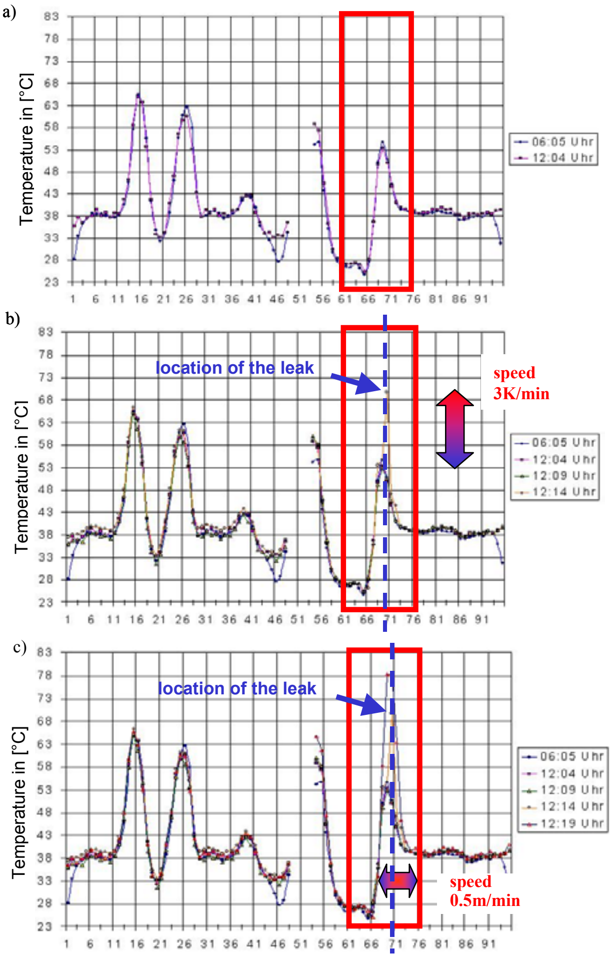


Fig. 1: Temperature evolution of a local leakage along a brine pipeline as a function of time; a) temperature profile before the leakage, b) the leak is identified by a local and rapid temperature increase, c) the temperature increase spreads at a speed of 0.5m/min.

Over more than 30 years, a wide range of fiber optics cable have been developed for telecommunication applications featuring high resistance to mechanical and chemical damage. The cables can integrate multiple optical fibers, can be placed directly in the soil or embedded in concrete. Moreover they are designed to operate over a wide temperature range (-50°C to 80°C) and can sustain pressure in excess of 75 MPa, which makes them very suitable for temperature monitoring. In addition to a long-term stability (the cables are constructed to last more than 30 years), the cables are designed to be insensitive to humidity, corrosion while the optical fibers are totally immune to electromagnetic perturbations. Finally the preparation and the installation of the sensing cable is extremely convenient and low-cost, since only one cable is unwound and placed along the pipeline compared to the installation of thousands of multiplexed pin-point sensors.

The detection of leakages along a pipeline through the control of the temperature requires a special processing in order to discriminate an actual leak from the environmental temperature fluctuations. The temperature evolution associated to a leakage has been extensively studied by the company GESO in Jena. GESO also addressed the positioning of the optical fiber with respect to the pipeline for different types of pipeline (hot water, oil, brine, phenol, gas, etc.). Fig. 1 shows the time evolution of the temperature measured by the sensing fiber placed underneath a brine pipeline as a leak occurs. Fig1a) shows that the temperature profile in the absence of leakage is not even at all. Therefore the detection of leakage is only possible through the analysis of temperature deviations with respect to a baseline profile (which may slowly evolve with time).

The local temperature in the vicinity of the leakage is modified in two steps. When the leakage occurs, a local temperature increase is first observed and in this case was measured to increase at a rate of 3°K/min (Fig.1 b)). Then the temperature increase starts to spread laterally at a speed of 0.5m/min. The processing of the temperature profiles takes into account this evolution in two steps in order to discriminate leakages from normal daily temperature variations. The efficiency of the technique has demonstrated the ability to detect leaks as small as 50ml/min in the case of brine and 10ml/min in the case of chemicals [1]. Moreover the technique enables the localization of the leakage with a precision in the range of one meter.

3. Raman and Brillouin fiber optics distributed sensing techniques

Raman and Brillouin scattering phenomena have been used for distributed temperature monitoring over the past few years. Raman was first proposed for sensing applications in the 80's [2], whereas Brillouin was introduced later as a way to enhanced the range of OTDR [7] and then for strain and/or temperature monitoring applications. Fig. 2 schematically shows the spectrum of the scattered light in optical fibers assuming that a single wavelength λo in launched in the fiber. Both scattering effects are associated to different moving non-homogeneities in the silica and have therefore completely different spectral characteristics.

The Raman scattered light is caused by thermally influenced molecular vibrations. Consequently the backscattered light carries the information on the local temperature where the scattering occurred. In fact the Raman backscattered light has two frequency shifted components: the Stokes and the Anti-Stokes components. The amplitude of the Anti-Stokes component is strongly temperature dependent whereas the amplitude of the Stokes component is not. Therefore Raman sensing technique requires some filtering to isolate the relevant frequency components and consists in the recording of the ratio between Anti-Stokes amplitude by the Stokes amplitude, which contains the temperature information. Since the magnitude of the spontaneous Raman backscattered light is quite low, high numerical aperture multimode fibers are used in order to maximize the guided intensity of the backscattered light. However, the relatively high attenuation characteristics of multimode fibers limit the distance range of Raman-based systems to approximately 10 km.

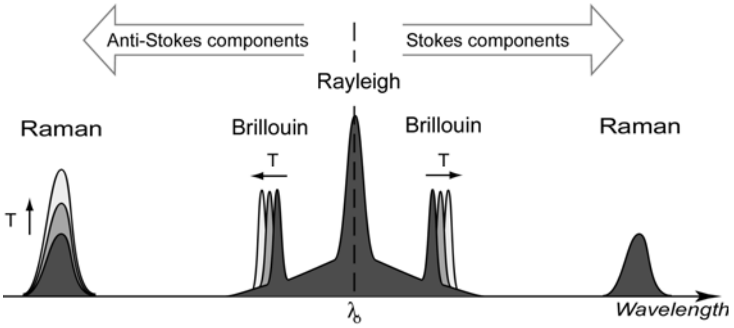


Fig. 2: Schematic representation of the scattered light spectrum from a single wavelength signal propagating in optical fibers. An increase of the fiber temperature has an effect on the both Raman and Brillouin components

Brillouin scattering occurs as a result of an interaction between the propagating optical signal and thermally acoustic waves in the GHz range present in the silica fiber giving rise to frequency shifted components. It can be seen as the diffraction of light on a moving grating generated by an acoustic wave (an acoustic wave is actually a pressure wave which introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift since the grating propagates at the acoustic velocity in the fiber. The acoustic velocity is directly related to the medium density and depends on both temperature and strain. As a result the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fiber. Furthermore, Brillouin-based sensing techniques rely on the measurement of a frequency as opposed to Raman-based techniques which are intensity based. Brillouin based techniques are consequently inherently more accurate and more stable on the long term, since intensity-based techniques suffer from a higher sensitivity to drifts.

Brillouin scattering has the particularity that it can become a stimulated interaction provided that an optical signal called the probe signal is used in addition to the original optical signal usually called the pump. This interaction causes the coupling between optical pump and probe signals and acoustical waves when a resonance condition is fulfilled, i.e. when the frequency difference between probe and pump light corresponds to the Brillouin frequency shift. It turns out that the resonance condition is strain and temperature-dependent, so that determining the resonance frequency directly provides a measure of temperature or strain. The advantage of measuring the interaction of two optical signals instead of recording the low intensity spontaneously scattered light is that the signal-to-noise ratio is much more comfortable. As a result, the measurement of spontaneous backscattered light required long integrating time, whereas the pump-probe technique doesn't and is therefore very suitable for rapid measurements.

Brillouin-based sensing techniques operates only with singlemode optical fibers and thanks to the low loss characteristics of singlemode fibers, measurements over several tens of kilometers can be achieved.

The localization of the temperature information along the fiber is possible by using a radar-like concept. Optical laser pulses are launched into the sensing fibers, while their interaction with the propagating medium is recorded as a function of time. Provided that the velocity of light in the fiber is known, the time information can be converted into distance and an actual temperature profile of the fiber can be computed. Thanks to the high speed of light, fiber lengths of several kilometers can be scanned within a fraction of second, yielding several thousands of measurement points. The spatial resolution is set by the pump pulse width or the equivalent distance occupied by half of optical pulse within the fiber (for instance a 10ns pulse yields a 1 meter spatial resolution along the fiber). Both Raman and Brillouin systems have demonstrated spatial resolution in the meter range.

In general, Raman systems operates well with multimode fibers, but have a limited distance range (up to 10km) whereas Brillouin-based sensing techniques works only with singlemode fibers and present much longer distance capabilities (beyond 50 km [6]). Both techniques can achieve accuracies below 1°K provided that the averaging time is properly set. Stimulated Brillouin scattering has demonstrated to offer a higher signal-to-noise ratio and higher quality measurements can be performed in shorter periods of time and therefore is more suitable for rapid measurements. Finally Brillouin-based systems can measure both strain and temperature, while Raman scattering is sensitive only to temperature.

Fig.3 Omnisens DiTeSt Analyzer for distributed temperature and strain measurement in optical fibers

4. The DiTeSt Analyzer - distributed temperature monitoring system using stimulated Brillouin scattering

Omnisens DiTeSt monitoring system was selected by the company GESO for the detection of leakages along a 55km brine pipeline. The DiTeSt is an innovative long range laser-based monitoring system based on the so-called Stimulated Brillouin Scattering (see Fig. 3) [9]. The inherent stability of the system comes from the use of a single laser source and a high speed electro-optic modulator for the generation of both pump and probe signals. The intensity of both optical signals can be controlled in order to have the highest possible signal-to-noise ratio and reduce the acquisition time. The frequency difference between pump and probe signal is precisely controlled by the modulation frequency applied to the electro-optic modulator, leading to 10^{-5} precision on the frequency determination. This frequency difference can be swept in the spectral range of the Brillouin frequency shift (10.5 to 11 GHz depending on the fiber type) so that the frequency response of the fiber can be determined. In other words the magnitude of the interaction between pump and probe is recorded at every location along the optical fiber.

The local Brillouin frequency shift (which contains the temperature information) is found to be at the maximum of the resonant interaction between both optical signals. A typical frequency response is shown in Fig. 4. The figure shows the frequency response of a 150m fiber section with and without a local hot spot. In Fig 4 b) the Brillouin component corresponding to the hot spot clearly stands out. The temperature dependence of the Brillouin frequency shift is found to be 0.927 MHz/deg at a 1.55 micron wavelength and for standard telecommunication fibers [8].

The DiTeSt system performs temperature profile measurement with a 1°C accuracy (defined as 3 times the standard deviation on repetitive measurements) and a spatial resolution of 1m over the first 10km and 2m up to 25 km. 50'000 distance points can be measured with a minimum sampling interval of 0.1m. The acquisition time (time to get one complete profile) may vary from 30 seconds to 5 minutes depending on the number of frequency points. Furthermore the DiTeSt system was developed for automatic and unattended monitoring over long period of time. It includes some self diagnostic and automatic restart and re-launch of the measuring agenda in the case of problems. The DiTeSt features two measurement channels thanks to an integrated optical switch in standard.

5. Leakage detection on a 55km brine pipeline case study

In 2002 the construction of a natural gas storage facility some 1500m under the ground surface was started in the area of Berlin in Germany. Using mining technology the building of underground caverns for gas storage in large rock-salt formation requires hot water and produces large quantities of water saturated with salt, the so-called brine. In most cases the brine cannot be processed on-site and must be transported by a pipeline to the location where it can either be used for chemical processes, or injected back safely into the ground. Because the brine can be harmful for the environment, the pipeline shall be monitored by a leakage detection system.

In the Berlin project a 55km pipeline was built and the company GESO was selected for the development and the installation of the leakage detection system. In order to cover the whole pipeline distance, it was decided to use two DiTeSt analyzers although one instrument would have been theoretically able to cover the whole distance with its two channels. However the installation of the fiber cable required some 60 splices (that correspond to a additional loss of up to3 dB) which reduces the distance range of the instrument accordingly and justified the use of two instruments. The selected sensing cable is a customized version of a standard armored telecommunication fiber optics cable for

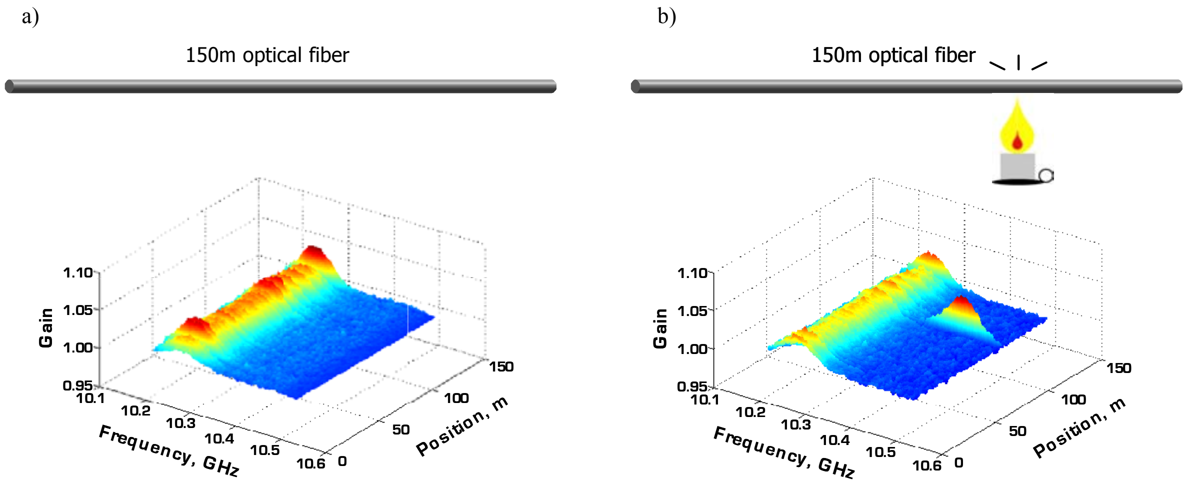


Fig.4: 3D representation of the position of the Brillouin Stokes component as a function of both distance and frequency of a 150m fiber section; a) fiber at uniform temperature; b) when a hot spot is introduced at a 120m position.

underground applications. The cable includes the optical fibers used for temperature monitoring as well as fibers for data communication between the instruments and the control room and additional spare fibers.

During the construction phase the fiber cable was first placed in the trench and buried in the sand some 10 cm underneath the pipeline. The position of the cable with respect to the pipeline is important in order to guarantee that all leakages are detected. The position of the sensing cable is a trade-off between the maximum contrast in the case of a leakage and the assurance to detect leakages occurring from every point of the tube circumference. The pictures in Fig. 5 show the construction of the pipeline before and after the pipeline was put in the trench.

Fig. 5 : Construction phase of a buried brine pipeline in the north-east area of Berlin. The fiber optics cable is placed in the sand at the 6 o'clock position about 10 cm underneath the pipeline .

The overall pipeline configuration together with the temperature monitoring system configuration is schematically depicted in Fig.6. Both DiTeSt instruments are installed in dedicated buildings (gate II and gate V respectively). Each instrument is responsible for the monitoring of half of the total distance and an optical switch is used to select the section to be monitored, so that the longest fiber section is 16,85 km. The central computer located in the control room in Rüdersdorf can communicate with the instrument through an optical LAN that makes use of available fibers of the sensing cable. The temperature profiles measured by both DiTeSt instruments are transferred every 30 minutes to the central PC and further processed for leakage detection.

A dedicated software developed by GESO runs continuously on the central PC and controls the complete monitoring system. It performs the leakage detection through a comparison between recorded temperature profiles, looking at abnormal temperature evolutions and generates alarm in the case of the detection of leakage. The system is able to automatically transmit alarms, generate reports, periodically reset and restart measurements, and requires virtually no maintenance.

The brine is pumped out from the underground caverns in Rüdersdorf and is injected into the pipeline at a temperature of about 35°C. At normal flow rate the temperature gradient along the whole pipeline length is about 8°C. Since the pipeline is buried in the ground at a depth of approximately 2 to 3 meters, the seasonal temperature variations are quite small and the soil temperature was measured to be around 5°C. As a result a substantial temperature increase is associated to every leakage even in the case of low leak rates.

The pipeline construction phase was completed in November 2002 and the pipeline was put into operation in January 2003. In July 2003, a first leakage was detected by the monitoring system. It was later found that the leakage was accidentally caused by excavation work in the vicinity of the pipeline. Fig. 7 shows the occurrence of the leakage and its effect on the temperature profiles as they were displayed on the central PC in Rüdersdorf control room. The graphs in Fig. 7 correspond to measured raw data, i.e. Brillouin frequency shifts, as a function of distance. By using the 0.927 MHz/deg temperature coefficient, the local temperature increase due to the leakage is measured to be 8°C. An alarm was immediately and automatically triggered and the flow was eventually stopped.

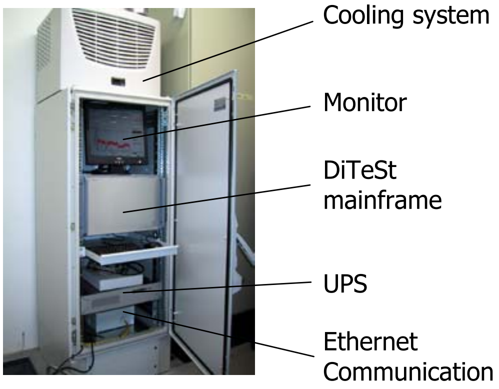


Fig. 7: Configuration of the rack integrating the DiTeSt analyzer together with dedicated UPS and cooling system. An optical Ethernet is used for the communication between the instruments and the central PC in the control room.

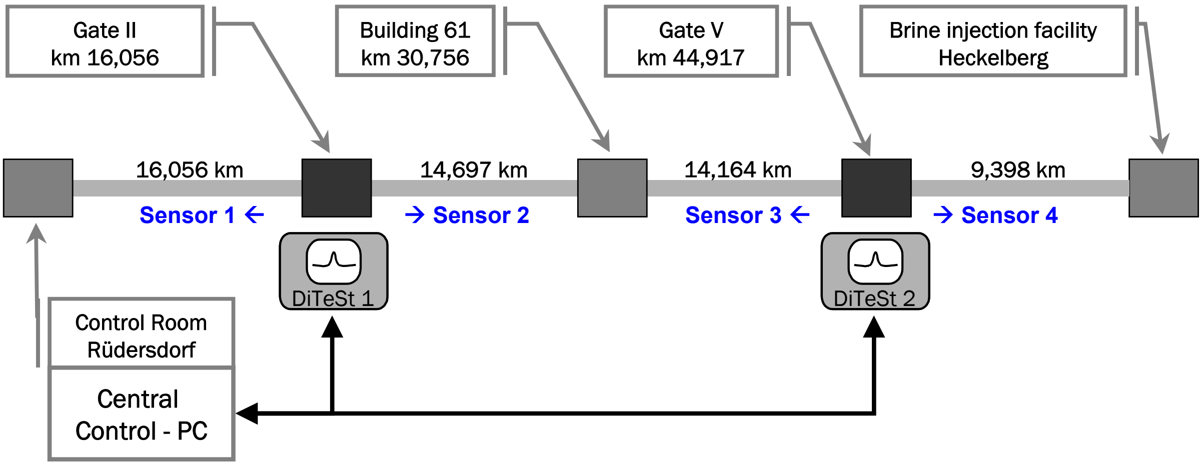


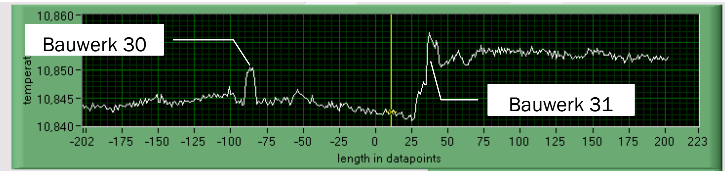
Fig. 6 : Schematic representation of the brine pipeline built to evacuate the brine from Rüdersdorf and transport it to Heckelberg where the brine in injected back into the ground. Both DiTeSt instruments have two measurement channels, respectively called sensor 1 to 4. The sensors temperature profiles are periodically transferred to the central PC for further processing and alarm generation.

6. Conclusions

Fiber optics distributed temperature sensing techniques have opened new possibilities in temperature monitoring and gradually have found applications in various domains such as civil engineering, the oil and gas, power plants, fire detection, etc. Their ability to precisely measure temperature evolution over several tens of kilometers and localize the information with a meter spatial resolution makes them very attractive for leakage monitoring applications. Leak rates as low as 50ml/min have been detected on a brine pipeline by temperature monitoring and identification of local temperature anomalies. Among today's available sensing techniques, Brillouin-based techniques have demonstrated the best performances in terms of distance range, accuracy and detection time. In the north-east of Berlin a 55km pipeline was equipped with a fiber optics leakage detection system during the construction phase of the pipeline in 2002 by the company GESO. Taking into account the application requirements in terms of distance range, and measurement time, neither Raman nor spontaneous Brillouin scattering techniques were applicable and only a stimulated-Brillouin-based system could perform an accurate temperature monitoring in the available time (monitoring of 55km with 1°C accuracy in less than 10 minutes). To-date the leakage detection system has been in operation for one year and one leakage was detected.

The performances of the stimulated-Brillouin-based systems in terms of acquisition time open new possibilities for fire detection of large structures such as tunnels, buildings, chemical plants thanks to the possibility to detect hot spot in less than a minute. Furthermore, new configurations are being investigated towards extending the distance range beyond 100km while maintaining a spatial resolution in the meter range.

Temperature profile before leakage



Temperature profile when the leakage is detected

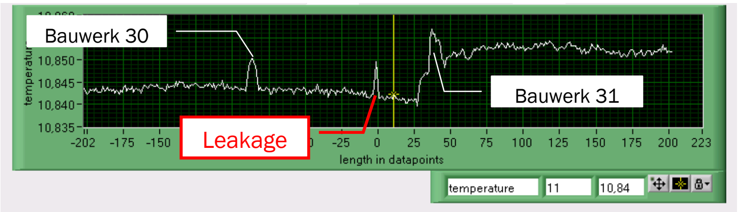


Fig. 8 Measured profiles before and after the leakage occurred at distance 17'970 meter from the pumping station, as displayed on the central PC in the control room. The vertical scale corresponds to raw Brillouin frequency shift given in GHz. The observed local temperature increase associated to the leakage was measured to be of around 8°C.

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