Light as a warning system

Dr. María A. Pimentel Niño, ILF Consulting Engineers, Germany, explains the use of optical fibres to detect leaks and geohazards.

Who hasn't ever enjoyed the blue sky on a sunny day?

Ancient civilizations like the Greeks did not have a name for the colour blue, even though they must have enjoyed clear blue skies just like us. An explanation to this oddity might be that blue objects other than the sky are actually quite rare to find in nature.

An apparently arbitrary optical phenomenon – light scattering in the earth's atmosphere – is responsible for producing the blue colour every (sunny) day for us. Moreover, the same phenomenon leads to attenuation, albeit undesired, in optical fibre communications, and it opens the door for fibre optic sensing to detect third party intervention, geohazards or leaks, with distributed acoustic sensing (DAS).

This article presents a short introduction to DAS technologies, current usage in pipeline monitoring, and particular considerations for installation and commissioning.

The keys to DAS

The blue sky – light scattering

In 1871, Lord Rayleigh first showed that the intensity of light scattered by particles much smaller than the wavelength of light is inversely proportional to the fourth power of its wavelength. This explains why the short-waved blue light, as part of our sunlight's spectrum, is scattered with higher intensity than sunlight components of longer wavelength, making the sky above look blue (Figure 1).

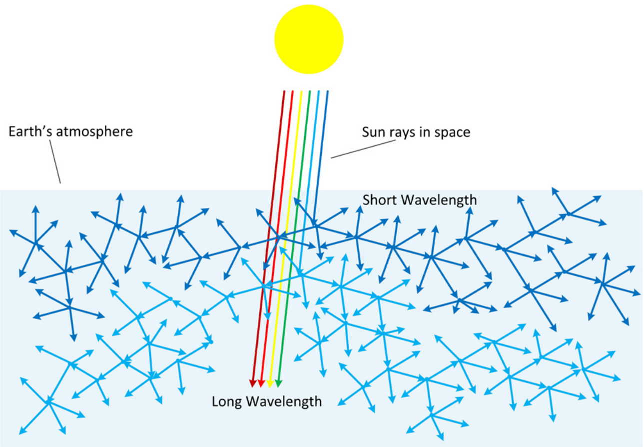

Figure 1. Sunlight scattering in the atmosphere.

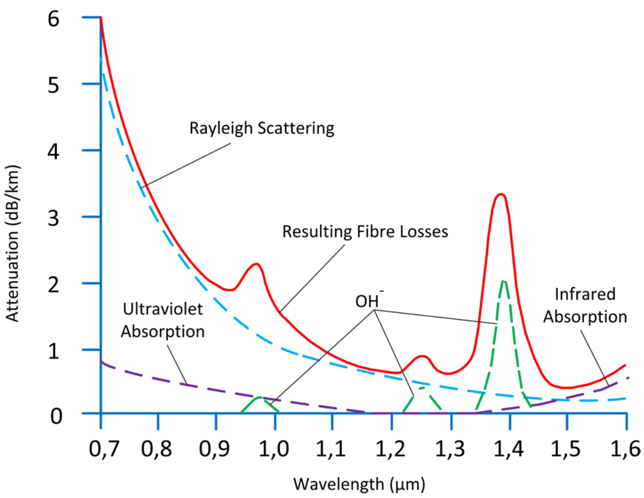

Figure 2. Causes of attenuation in optical fibres.

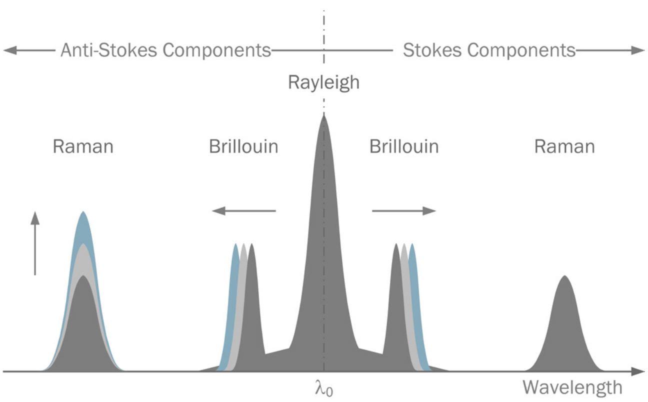

Figure 3. Frequency response of backscattering light.

Rayleigh scattering is dependent on density fluctuations and impurities – called scattering centres – of the medium (e.g. the atmosphere, an optical fibre), altering its refractive index. For this reason, Rayleigh scattering is one of the dominant sources of loss in optical fibres used for long distance data transmission (Figure 2). However, its dependence on external conditions helps in considering the fibre as a sensing device.

In comparison with other types of light scattering in Figure 3 (used by long-established distributed temperature sensing, DTS)[4], the intensity of Rayleigh's scattered light is higher, and its wavelength is the same as that of the incident light.

How do you listen to the fibre?

DAS is a distributed fibre optic sensing (DFOS) technique that takes advantage of Rayleigh scattering and the acoustic sensitivity of the fibre. By means of advanced optical time domain reflectometry (OTDR) and interferometric principles, DAS is able to detect acoustic perturbations just by using one single fibre and one active interrogator on an end of the fibre.

An OTDR device sends laser-generated narrow light pulses through the fibre and captures the backscattered response with a photodetector. The pulse is backscattered each time it encounters a scattering centre along the fibre (Figure 6). The intensity of the returned pulses is integrated as a function of time, providing a graphical representation of the characteristics of the fibre over its entire length (Figure 4).

When an acoustic perturbation is sensed at any given section of the fibre (Figure 5), a dynamic strain in the scattering centre is generated, translating into amplitude and phase shifts in the backscattered signal. With interferometric analysis – the study of super positioned signals received over time – the phase and frequency shift cues can be interpreted to indicate location of the acoustic source along the fibre, as well as the type of source (e.g. a digging machine, soil movement).

DAS relies on complex optical and digital signal generation, capturing and processing. Highly narrow coherent laser sources, state-of-the art photodetectors and amplifiers handle the optical signal combined with the latest detection techniques, such as coherent C-OTDR or Phase-OTDR.[2]

DAS today – applications for pipeline monitoring

Use cases

Due to the fibre's sensitivity to vibrations, strain and temperature changes, it is ideal in detecting and identifying leaks, hot or cold spots, sources of third party intervention and geohazards. Applied over the lengths of a test object, the fibre acts as a distributed sensor, making it a perfect means for monitoring pipelines, long perimeters or power cable networks.[1,3]

DAS can generate alarm events for specific already-classified sources of perturbations. Liquid and gas pipelines can be monitored for leaks through detection

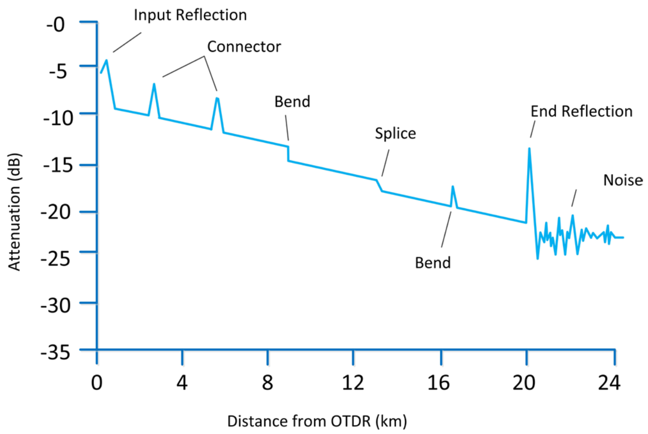

Figure 4. Analysis of fibre losses using OTDR technology.

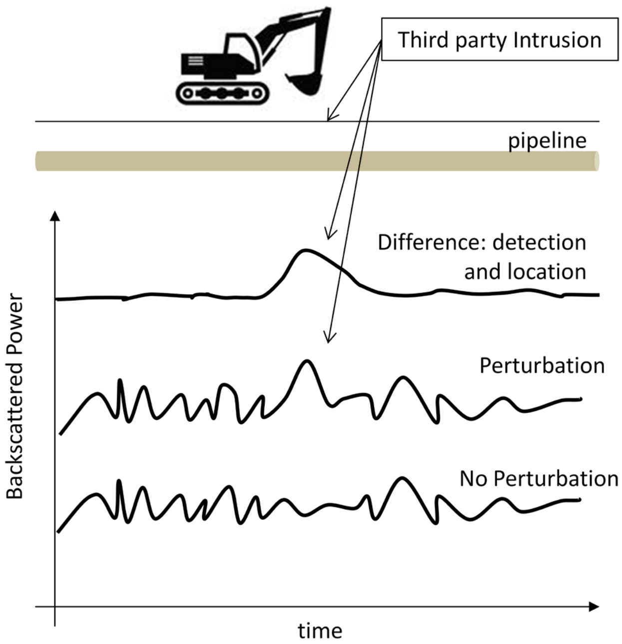

Figure 5. Intrusion detection through DAS.

of temperature gradients, negative pressure waves, and orifice noise.

According to a study released by the Fiber Optic Sensing Association (FOSA), 13.5% of the 33 000 km of assets monitored by DFOS worldwide corresponds to pipelines.[7] DAS is one of the technologies used in many of these installations.

Performance

The guidelines for Computational Pipeline Monitoring (CPM) from the American Petroleum Institute API 1130, although meant for internal leak detection systems, shall serve as a guide to measure the performance of DAS.[5] Table 1 shows CPM metrics and how DAS performs.

Security

DAS is a robust technology providing detection of unsolicited excavations, hot tapping or natural disasters. However, other threats to system integrity and availability that come from various sources, including cyberattacks or human errors, may impact all levels of security, including the adequate performance of DAS. Therefore, a security master plan is required, resulting from a holistic, systematic and integrated secure-by-design approach to tackle threats faced by pipelines.[6]

Practical matters in DAS – does the cable matter?

To protect them from external environmental forces and material degradation, the fibres are coated with layers of different material and protective tubes, forming a fibre optic cable (FOC).

Further, below ground FOC installations inside ducts (as opposed to direct burial) have become common practice, in order to protect the cable and simplify later reparations and upgrades. In pipeline installations, cable ducts are ideally installed in the same trench as the pipeline, and the cable is blown or pulled into the duct at a later stage without affecting the pipeline or need to dig in.

The basic requirement for the FOC installation of DAS is 'acoustic coupling' – maximise the sensitivity of the fibre so that it is able to 'listen' to the acoustic signals that represent a strain, leak, or ground movement. The combined effects of certain cable compositions and its installation can lead to a weak sensitivity of DAS.

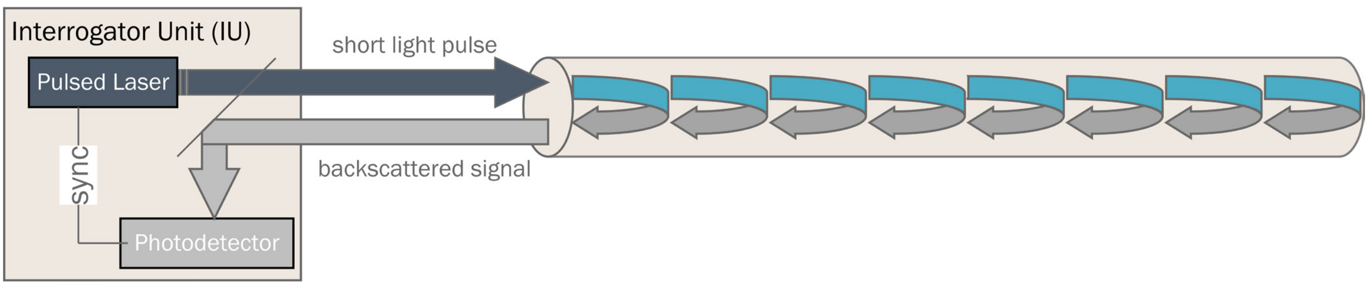

Figure 6. A DAS Interrogator Unit receiving backscattered signals from the fibre.

However, trade-offs that guarantee the performance of DAS, protect the cable, and simplify the installation are possible. Cable construction with loose tube and gel filled water blocking provides the necessary cable robustness (as opposed to tight buffer cable) with better dynamic strain and acoustic coupling than no gel options. Cable installation inside a duct is an acceptable compromise to protect the cable, instead of direct burial with metallic armouring for rodent protection, which may attenuate the acoustic signals more than duct installation.

Figure 7. Pipe trench with FOC laid at 2 o'clock.

The latest DAS technologies in the market are also able to perform using FOC commonly used for telecommunications – a very convenient synergy that allows the use of the same cable both for sensing purposes as for data transmission. Cable manufacturers also offer hybrid tailor-made cable constructions for more complex sensing and communications purposes.[8]

Case study: Commissioning of DAS for pipeline monitoring

ILF Consulting Engineers recently supervised the commissioning activities of a 292 km, 42 in. gas pipeline in Latin America, including, amongst others, a pipeline monitoring system (PMS).

PMS system specifications

The PMS was a Rayleigh based DAS system for detection of third party intervention (digging, excavation), geo-hazards (landslides, seismic movement events) and leaks. It used only one sensing optical fibre and two additional fibres for data communications, with bandwidth requirements of 22 Mbps. These were all part of the common FOC for telecommunications and control systems, blown into a duct laid along the pipeline in the same trench.

With coverage of roughly 40 km per interrogator unit, the PMS architecture was designed to have two interrogator units every 80 km, installed with processing and networking equipment in the respective pipeline stations. The system included dedicated operator

Table 1. Performance of DAS against API 1130 metrics

	API definition	Translation to DAS	Current DAS performance
Sensitivity	Minimum intensity and time required for an event to be registered.	Dynamic range of the perturbations that can be detected.	Dynamic strain sensed by the fibre in order of nm. Location of FOC with respect to pipeline also affects sensitivity.
		Response time.	Subject to fibre length (order of µs for 40 km fibre), propagation of speed of sound, and computational processing. Early and fast detection through the acoustic sensing (prior to actual leak). Leak detection within 1 - 10 min.
Accuracy	Precision in the events detected.	Spatial resolution: uncertainty margin along the fibre.	Event detected with ±10 m over a 40 - 50 km long fibre in current solutions.
		Type of events detected and error margin.	Manual or mechanical digging, personnel walking, vehicles, fibre breakage, leaks.
Reliability	System should not generate false alarms.	Probability of false alarms.	System is tuned at commissioning stage to adapt to particularities of location and reduce false alarms.
Robustness	Ability to provide useful information even if conditions of pipeline operation change, or if data is lost.	Fibre robustness.	Fibre is immune to electromagnetic interference; same FOC used for telecommunications can be utilised.
		System robustness.	If fibre breaks continue to function upstream of the break; can be used in conjunction with other solutions; early and fast detection through acoustic sensing; can detect events occurring simultaneously but spatially separated along the fibre.

Figure 8. Position of FOC at 12 o'clock.

workstations in control operator rooms and interfaces to the control system via Modbus TCP/IP.

The location of FOC was optimised to guarantee: 1) reliable gas leak detection and 2) accessibility to the pipe for maintenance purposes without affecting the FOC.

The optimal position chosen was at 2 o'clock, with a distance of 30 - 50 cm between the FOC and the pipe (Figure 7). A location prioritising gas leak detection only would be at 12 o'clock (Figure 8).

Recommendations

Following lessons learned can help for a smooth commissioning phase of a DAS based PMS.

- Identification of clear interfaces between the PMS supplier and the suppliers/contractors of other systems sharing the same FOC.
- Co-ordination during design and construction with the PMS supplier regarding changes in the position of the FOC at crossings, such that the integrity and reliability of the system can still be guaranteed.
- Involvement of PMS supplier in FOC installation and attendance to FOC testing, in order to guarantee that the fibres of the FOC used for DAS meet the necessary requirements for proper functioning of the PMS.
- Close co-ordination with other contractors/vendors to optimise the installation and commissioning schedule, as well as to establish priorities in pipeline operations (which system shall be functioning first) in order to avoid works in the FOC along the pipeline at later stages when the normal functioning of the pipeline systems may be compromised.
- Planning schedule for calibration of the system. Use-case specific tuning of the system is needed to decrease the probability of false positives. This phase may take at least a month, depending on the supplier.

Conclusion

DAS is a highly advanced technique suitable for enhanced pipeline monitoring alone, or in conjunction with other established computational PMSs. Practical aspects in DAS implementation, installation, and commissioning as part of a pipeline project must be addressed to take full advantage of this technique as a building block in a complex pipeline system. As a solution for monitoring of physical security, DAS should also be considered as a part of the bigger picture in critical infrastructure protection, where it can definitely bring added value for a security master plan.

Note

Part of this article was presented at PTC (Berlin 2017).

References

1. BAO, X., and CHEN, L., 'Recent progress in distributed fiber optic sensors,' Sensors, Vol. 12, No. 7 (2012), pp. 8601 – 8639.
2. PALMIERI, L., and SCHENATO, L., 'Distributed optical fiber sensing based on Rayleigh scattering,' The Open Optics Journal, No. 7 (2013), 104 – 127.
3. WILLIAMS, J., 'Distributed Acoustic Sensing for Pipeline monitoring,' Pipeline & Gas Journal, Vol. 239, No. 7 (July 2012).
4. FRINGS, J., and WALK, T., 'Distributed Fiber Optic Sensing Enhances Pipeline Safety and Security,' Oil Gas European Magazine, Vol. 37, No. 3 (2011), pp. 132 – 136.
5. KASCH, M., 'A selection guide for leak detection systems,' World Pipelines, Vol. 15, No. 2 (February 2015).
6. BARTH, M., Critical infrastructure protection in Europe, Proceedings of GIE, Brussels, 16 November, 2016.
7. Fiber Optic Sensing Association. https://www.fiberopticsensing.org.
8. FREELAND, RS., CHOW, B., WILLIAMS, J., and GODFREY, A., 'Relative acoustic sensitivity of standard telecom and specialty optical fiber cables for distributed sensing,' Proceedings of SPIE, Fiber Optic Sensors and Applications XIV, Vol. 10208 (April 2017).