DAS: Pipeline Monitoring and the Blue Colour of the Sky

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Abstract

Taking advantage of the same phenomenon that allows us to see the sky as blue, Distributed Acoustic sensing (DAS) is the most novel technique for safe and efficient pipeline monitoring. DAS offers the possibility of reading the fingerprint of an entire pipeline at the speed of light by using fibre optic cable as spatially distributed sensor elements. Some of its applications include detection and identification of third-party intervention, geohazards and leakages. Furthermore, DAS offers synergies by using the existing telecommunications infrastructure, if the fibre optic cable is laid along the pipeline. This article presents the technical aspects behind DAS and the scenarios where pipeline monitoring can benefit from it, a performance analysis, and a glimpse of DAS as part of a holistic approach to security of critical infrastructure. Finally, a case study is presented on the commissioning of DAS for a gas pipeline.

1 Introduction

Who hasn’t ever enjoyed the blue sky on a sunny day putting a bounce in our steps?

Though many ancient civilizations – including the Greeks, Chinese, Japanese, and Hebrew – must have enjoyed shiny sunny days like us, no name for the color blue existed for them. An explanation to this oddity might be that blue objects other than the sky are actually quite rare to find in nature, thus challenging the making of blue dyes at that time.

An apparently arbitrary optical phenomenon –light scattering in the earth’s atmosphere– is actually responsible for producing the blue color every (sunny) day for us. In optical fibres – a core piece in modern high speed communication networks – the same phenomenon leads to (undesired) attenuation in end-to-end communications, but at the same time is useful to track the entire path of the fibre.

Pipeline monitoring can also benefit from light scattering in the optical fibre. The acoustic sensitivity of the fibre and the possibility of “listening” to the optical effects caused by vibrations by analyzing scattered light has led to the name Distributed Acoustic Sensing (DAS). DAS is an attractive external detection system for pipeline monitoring. The sensor (the fibre) is laid along the pipeline, monitoring its entire length for third party intervention and geo-hazards, acting as an effective sensing system for possible leakage as well.

This article presents a DAS primer, with its principles and techniques, together with examples of what can be done with DAS today, and how it can be seen as a building block of a more complex plan to ensure infrastructure security. More academically oriented surveys on the state-of-the-art and details behind DAS are discussed in [1][2][3][4][5].

2 The keys to DAS - From the blue in the sky to third-party intrusion detection

2.1 The blue sky –Light Scattering

When sunlight streams through the earth’s atmosphere, part of it is scattered in every direction by the atmosphere’s particles. The blue light, part of the sunlight’s spectrum, is scattered with higher intensity than sunlight components of longer wavelength. Thus, as shown in Figure 1, the sky above looks blue.

Such phenomenon is known as Rayleigh scattering after Lord Rayleigh John William Strutt, (1842 - 1919). He first showed that the intensity (I) of light scattered by particles much smaller than the wavelength of light is inversely proportional to the fourth power of its wavelength, (λ), $I=f(\lambda^{-4})$. Moreover, scattering is dependent on density fluctuations- called scattering centres- in the medium, altering the medium’s refractive index.

Figure 1 Sunlight scattering in the atmosphere

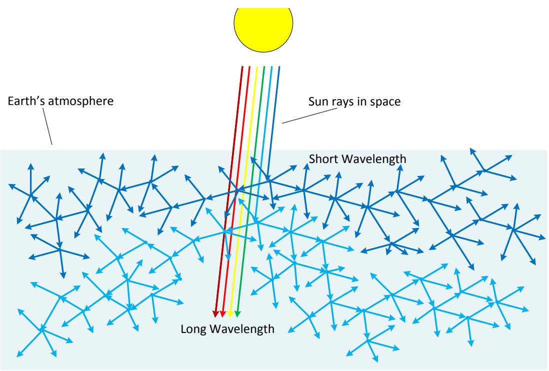
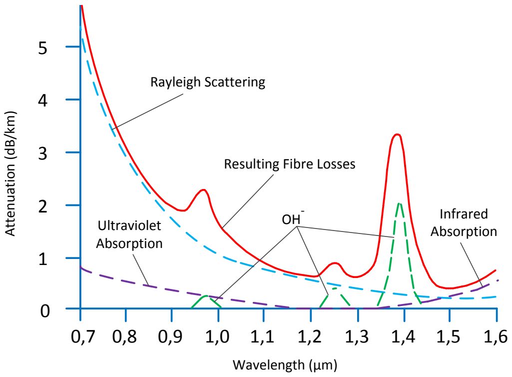


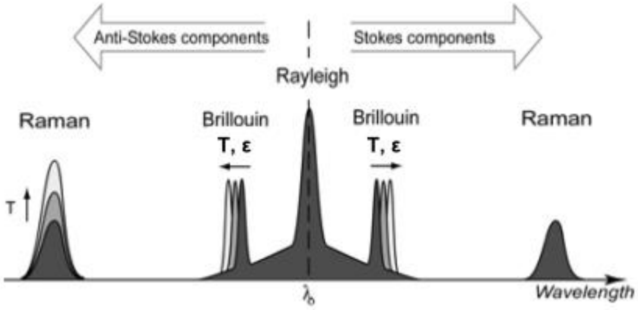
Figure 2 Causes of attenuation in Optical Fibres



The optical fibre, like the atmosphere, is not devoid of impurities, and scattering and absorption of light occurs. As Figure 2 shows, Rayleigh scattering is one of the dominant sources of loss in optical fibres, the limiting factor for data transmission over long distances. However it has been shown that its dependence on external conditions can be an advantage in the development of the optical fibre as a sensing device. In particular, acoustic disturbances cause vibrations in the fibre, in the form of dynamic strain oscillations. The vibration frequency and intensity can help in identifying the type of disturbance. Additionally, Rayleigh scattering is also affected by temperature changes.

Other types of scattering sensitive to external phenomena are present beside Rayleigh scattering. The well-established technology Distributed Temperature Sensing (DTS) uses Raman scattering to measure absolute temperature and Brillouin scattering to measure temperature changes and strain (See Figure 3 [13]). Rayleigh however, offers two advantages that translate into lower noise and less complexity when detecting backscattered signals. On one hand, the intensity of Rayleigh’s scattered light is much higher than other spectral components of scattered light. On the other hand, there are no frequency shifts between the incident light and the Rayleigh scattered light, for which Rayleigh is classified as elastic scattering, while Raman and Brillouin are classified as inelastic scattering.

Figure 3 Frequency response of backscattering light. (From [12])



2.2 How to listen to the fibre?

As light propagates along the fibre, it is altered by the fibre’s internal dynamics, and its backscattered light carries this information about a couple of physical parameters of the entire fibre strand, acting as a linearly distributed sensor. How can we capture the light that has travelled along the fibre?

2.2.1 Interferometry

Classical optical interferometry refers to the superposition of two optical signals, in order to extract information from them. The analysis of interference between the waveforms can give cues of phase or frequency shifts, or changes in intensity, which represents changes along the path of the optical signal. A classic application using optical fibres would send two pulses through two different fibres and superimpose them at the receiver end.

One of the early approaches to detect vibrations along the path of a fibre optic cable in fact used the above approach, with a Mach-Zehnder interferometer [10]. Two fibres carried one continuous wave each to a receiver, and a third fibre carried the superposition of the two waves back to the source for analysis of the wave’s interference pattern.

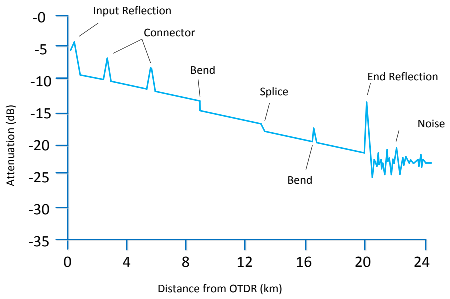
2.2.2 Reflectometry

Reflectometry is basically a non-invasive optics technique that enables the analysis of the properties of a medium by using the light reflected back from it.

In the time domain, optical time domain reflectometry (OTDR) is used to relate backscattered light signals to locations along the fibre strand. OTDR sends laser-generated narrow light pulses from a laser through the fibre and captures the backscattered response through a photodetector.

OTDR devices integrate the intensity of the returned pulses as a function of time, and, by knowing the fibre specific speed of light, plot it as a function of fibre length like shown in Figure 4. An OTDR device therefore acts like one-dimensional radar providing a graphical representation of the characteristics of the fibre over its length.

Figure 4 Analysis of fibre losses using OTDR technology



In the frequency domain, Optical Frequency Domain Reflectometry (OFDR), uses continuous waves as test signals to send along the fibre, generated from a frequency-tuneable laser, to analyse the frequency response of the backscattered signal.

OTDR and OFDR offer different sensitivity lengths, useful in different scenarios of optical sensing.

2.3 Detecting events along the fibre

In this article we focus on detection techniques suitable for long distance optical fibres that are applicable to pipeline monitoring. The exhaustive surveys [1], [2] present the state-of-the-art trends in broad distributed fibre optic sensing methods and applications. For instance, frequency domain reflectometry techniques are quite successful but are more suitable for short distance fibre lengths.

Additionally we focus on DAS as the technology that uses only one fibre and the need of only the interrogator as active component. Other solutions for vibration detection branded Distributed Vibration Sensing [10], use two or three fibres and active equipment at both sender and receiver ends.

DAS takes advantage of Raleigh scattering and the acoustic sensitivity of the fibre, and by means of advanced OTDR techniques and interferometric principles is able to detect acoustic perturbations.

2.3.1 Model for DAS

Let us model an optical fibre as a discreetly sectioned strand, with each section containing scattering centres, any microstructure that can cause light scattering. In this simplified abstraction, as a light pulse propagates along the fibre, a portion of it is backscattered, and very specifically for the individual fibre from each of the scattering centres as shown in Figure 5. The intensity of the backscattered signals is captured by a photo-detector at the sender side. Acoustic vibrations affecting the fibre generate microscopic changes (perturbations), which cause a change in the distance between the scattering centres that can be measured.

Figure 5 The optical fibre divided into discrete sections, showing the backscattered signals

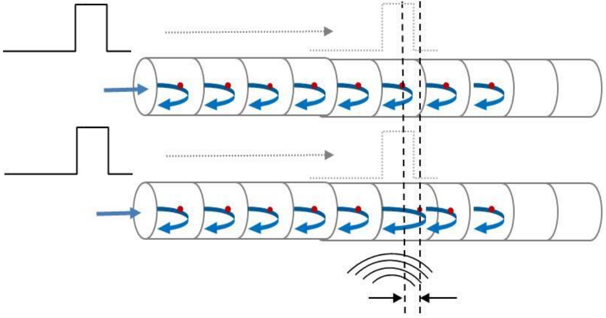
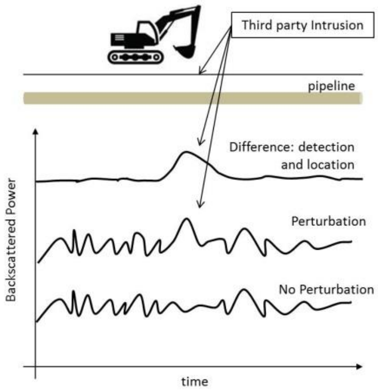


Figure 6 Intrusion Detection through DAS



If a perturbation is sensed at any given section of the fibre (see Figure 6), the dynamic strain of the scattering centre will generate a phase shift in the backscattered signal. In a simplified manner, if we consider only two adjacent sections of the fibre, the intensity of the superposition of their backscattered signals, described by the interference equation, would be characterized by the sum of amplitudes and the phase difference. Under normal circumstances, no perturbations, the phase shift will remain constant. However when perturbations at any of the two sections occur the phase shift will vary.

Additionally, the external vibration, seen as dynamic strain of the scattering centres, transfers its vibration frequency as well. Through an analysis of the variation of phase shifts over consecutive backscattered signals, this frequency can be captured.

Normally, a series of light pulses is used to probe the fibre. The repetition frequency of the pulse has to be such that there is sufficient time for the light pulse to traverse the entire fibre and for its complete backscattered signal to arrive at the sender before a new pulse is launched.

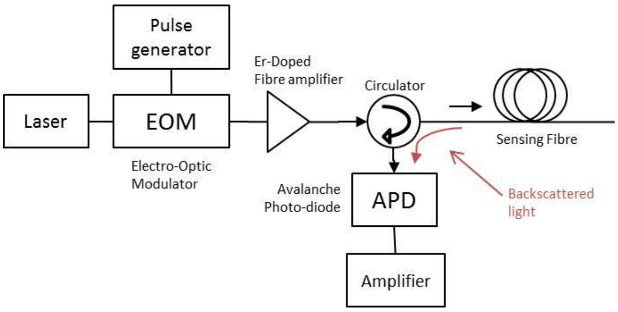
2.3.2 Challenges

The challenges of DAS lie in 1) capturing the Rayleigh backscattered signal with the least noise possible- high sensitivity, 2) complexity of processing numerous traces from the entire fibre strand in order to capture the necessary amplitude and phase information.

In order to solve 1), care must be taken in the generation of the light pulse by using a highly coherent source with narrow linewidth and state of the art optical launch amplifiers. The back-scattered light must be detected by state of the art photodetectors. Detection techniques, such as direct detection, as in phase-OTDR (see Figure 7), or that provide a higher dynamic range, as in coherent detection (C-OTDR), mitigate noise and guarantee sensitivity.

The complexity of processing numerous traces is mitigated with latest digital signal processing techniques and state-of-the-art processor and storage capabilities. Nevertheless, it implies the consideration of sufficient space for the installation of the necessary DAS processing equipment on site, which may amount to at least twenty 19” rack units (see Figure 9).

Figure 7 Direct detection phase-sensitive OTDR block diagram [3]



2.3.3 Identifying the source

Once the cues for DAS are captured, the signals are processed to identify the source of perturbation along the fibre. This involves a great deal of signal processing, mostly done through digitalized version of the optical signals captured.

The outcome is a number of alarm events for specific already classified potential sources of perturbations (a digging machine, movement in the soil, among others). This is possible by extracting the vibration frequency of the identified perturbation among other descriptors.

Use-case specific tuning of the system for particular threats according to a pre-established normal state is always needed to decrease the probability of false positives.

3 What can we see with DAS today – applications for pipeline monitoring

3.1 Use cases

Due to the fiber’s sensitivity to vibrations and heat changes, it is ideal in detecting and identifying leaks, hot or cold spots, sources of third party intervention and geo-hazards. Its length and operation as a distributed sensor make it a solution for a highly dense distributed sensing system for monitoring pipelines [4], long perimeters or power cable networks.

With only one fibre optic cable laid along the pipeline, DAS can detect third party intrusions like digging or excavations, the pressure waves of a pipeline leakage, ground movement and structural variations [12] [6][7][8][10][15][16].

3.2 Performance

In order for DAS to provide any added value in the area of pipeline monitoring, it must satisfy certain performance criteria specific to this application. The guidelines for Computational Pipeline Monitoring (CPM) from the American Petroleum Institute API 1130, serve as general considerations for DAS design [13].

According to API1130, DAS would be classified as an external leak detection system. However, the guidelines for CPM serve as guide to measure the performance and value of DAS. Table 1 shows CPM metrics and how DAS performs.

Important engineering aspects in the deployment of DAS are worth considering and discussed in [12].

Table 1 Performance of DAS against API 1130 metrics

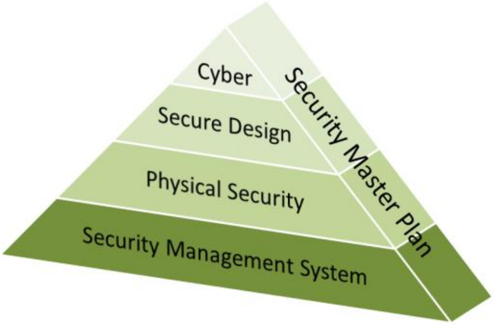
API Requirement	*API Definition*	*Translation to DAS*	*Current DAS performance*
Sensitivity	Minimum intensity and time required for an event to be registered	Dynamic range of the perturbations that can be detected.	Dynamic strain sensed by the fibre in order of nm. Location of FOC with respect to pipeline also affects sensitivity.
		Response Time	Subject to fibre length (order of µs for 40km fibre), propagation of speed of sound, and computational processing
Accuracy	Precision in the events detected	Spatial resolution: uncertainty margin along the fibre	Event detected with 10m spatial resolution over a 40-50km long fibre in current solutions.
		Type of events detected and error margin	manual or mechanical digging, personnel walking, vehicles, fibre breakage, leakage detection within 1 -10 min
Reliability	System should not generate false alarms	Probability of false alarms	System is tuned at commissioning stage to adapt to particularities of location
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 used for DAS
		System robustness	if fibre breaks continues 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

3.3 Security

DAS is a robust technology providing detection of unsolicited excavations, hot-tapping, terrorism or natural disasters. However, these are not the only threats faced by pipeline systems. Threats to system integrity and availability coming from various sources including cyber-attacks, or human errors may impact all levels of security, including the adequate performance of DAS. For this reason a holistic approach to protect infrastructure is desirable. [14]

By approaching security in a systematic and integrated fashion, the different threats faced by pipelines are tackled with a Secure by Design approach, in an interdisciplinary fashion. Figure 8 shows the proposed approach in [14] for a holistic security master plan.

Figure 8 Holistic approach to security of critical infrastructure [14]



4 Case study- Commissioning of DAS for pipeline monitoring

ILF Consulting Engineers recently participated in the supervision of commissioning activities of a 292 km 42” gas pipeline in Latin America. Activities included commissioning of telecommunications system, the fibre optic system, and the pipeline monitoring system (PMS), among other control and process systems.

4.1 PMS requirements

From the design phase, the main requirements for a PMS were defined as: a fibre optic based system for detection of gas leaks, third party intervention and geotechnical events. The fibre optic cable (FOC) was shared with the telecommunications system. The PMS was the only gas leak detection system to be used. Additional requirements included the possibility of simultaneous PMS data presentation at multiple operator rooms, alarm generation with priority levels, and integration with a Data Control System (DCS).

4.2 PMS Solution

The PMS solution chosen for the project was an integrated PMS using only one sensing optical fibre and two additional fibres for system data communications, all part of the common FOC for telecommunications and control systems laid along the pipeline in the same trench.

4.2.1 Sensing technology

The PMS solution was a Rayleigh based DAS for detection of Third Party Intervention (digging, excavation), Geohazards (landslides, seismic movement events) and Leaks (Temperature Gradient, Negative Pressure wave, orifice Noise).

4.2.2 System architecture

With coverage of roughly 40 km per interrogator unit, the architecture was designed to have two interrogator units every 80 km, rack mounted with necessary processing and networking equipment, installed in the respective pipeline stations (see Figure 9). Dedicated PMS operator workstations were installed at operator rooms, at the beginning and end of the pipeline, and interfaced to control system via Modbus TCP/IP. System bandwidth requirements were 22Mbps.

Figure 9 PMS rack mounted equipment at one of the block valve stations

4.2.3 FOC location

The location of FOC, blown into a duct, in the trench was optimized to guarantee 1) reliable gas leak detection 2) accessibility to the pipe for maintenance purposes without affecting the FOC. The optimal position chosen was at 2 o´clock, as shown in **Figure 11**, with a distance from 30cm to 50cm between the FOC and the pipe. A location prioritizing gas leak detection only would be at 12 o’clock as shown in **Figure 10**.

Figure 10 Position of FOC at 12 o’clock

Figure 11 Pipe trench with FOC laid at 2 o´clock

4.3 Recommendations for commissioning of PMS

Considering the technical requirements for proper functionality of PMS as well as the different interfaces with other systems, following lessons learned can help for a smooth commissioning phase.

- Identification of clear interfaces points with the suppliers/vendors of other systems sharing the same FOC, in first instance the FOC installation contractor, and the telecommunications contractor.
- Considering the sensitivity of the optical fibre as sensing element, and its installation along the pipeline, the involvement of DAS supplier by construction supervision during FOC installation and FOC testing phase on-site is recommended. In this way it can be guaranteed that the fibres used for DAS meet the necessary requirements for proper functioning of DAS.
- Close coordination with telecommunications systems vendor/installer and FOC installation contractor, to optimize the installation and commissioning schedule, and establish priorities in pipeline operations (which system shall be functioning first) in order to avoid re-splicing and testing the FOC for DAS along the pipeline after “gas-in”, where the normal functioning of the pipeline systems may be compromised.
- Planning schedule for calibration of the system. Depending on the supplier of the PMS and the difficulty to access the pipeline locations, calibration may at least take one month.
- Coordination with 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.

5 Conclusion

Distributed Acoustic Sensing is a highly advanced technique suitable for pipeline monitoring that has gaining maturity and relevance in recent years. It brings the advantages of well-established distributed fibre sensing techniques, with a wider range of capabilities. The detection techniques used in DAS enable the identification of leaks, third party intervention, geo-hazards among others, with attractive features in terms of detection time and location accuracy. As a solution for monitoring of physical security, DAS can 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.

6 References

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