Early Leak Detection and TPI Monitoring for Pipelines – Presenting a Practical Experience with Distributed Optical Fiber Sensing

Edward Tapanes, Li Xiaotong > Fibersonics Inc.

Abstract

The Oil & Gas pipeline industry is facing a very serious challenge in assuring spill and accident-free operations of pipeline infrastructure, which is distributed across many thousands of miles in both remote and populated areas. In recent years, however, the occurrences of high-profile spills and incidents have spiked, further escalating the safety concerns. [1] [2] For example, the San Bruno, California, explosion or the huge area of contamination by crude oil in Michigan's Kalamazoo River (a 4.3 million liter crude oil spill from a pipeline that is estimated to have cost $820 million to clean up). In Alberta, Canada, spills have occurred on average twice daily since 1975, at times resulting in high-profile large gas explosions and oil spills. [3] To help meet the challenge of a zero-incident target, the Oil & Gas industry must improve its range of technologies and ability to monitor their systems for safety in real-time – permanently and distributed along the length of the pipeline network. [4] One particularly promising technology involves the use of distributed optical fiber sensing cables. Over the past twenty years, several first and second-generation monitoring technologies were developed using fiber optic sensing cables for detection and location of leaks and third-party interference (TPI) events involving physical disturbance to the pipeline. [4] [5] [6]

To address the urgent need of the Oil & Gas industry for improved technology for securing and monitoring pipelines, Fibersonics has developed and patented a new generation of fiber optic technology – the technology is named "Long Ranger™". This technology can be very effective in the prevention of oil spills and/or gas explosions due to its unique ability to utilize an ordinary optical fiber cable to both detect, locate and classify vibrations caused by physical activity (such as TPI), while simultaneously monitoring for early-stage leaks, along the entire length of the pipeline in real-time. Over the past 5 years, Fibersonics has been working together with their regional partner in the P.R. China to implement several pipeline monitoring systems with local operators. This paper briefly presents some of the cases of implementing this technology on operational pipelines in P.R. China.

1. BACKGROUND

According to the analysis and statistics of pipeline accidents for the past 50 years, the main types of incidents involving the safe operation of oil and gas pipelines are leakage, TPI, blockages, displacement, and geological disasters, etc. The causes of these events are varied, and the resulting losses can often be huge. [2] [3] In order to maintain a safe and efficient operation, it is necessary to carry out real-time monitoring of operational pipelines to detect, find, analyze and treat all kinds of hazardous events as early as possible.

At present, manufacturers and scientific research institutions around the world have developed a variety of equipment to detect pipeline leaks and TPI. There is a vast multitude of products in the market. [4] Distributed optical fiber sensors are one promising type of technology to have emerged over the past 20 years. [6] Several first and second-generation monitoring technologies were developed using fiber optic sensing cables for detection and location of leaks and TPI events involving physical disturbance to the pipeline. [4] Earlier versions of this technology were able to monitor pipelines for many miles, but there were some significant drawbacks. These technologies may be broadly classified as follows:

1. First-generation locating interferometers, otherwise known as transmissive distributed fiber-optic vibration sensing (DVS) systems. [7] [8] [9] [10] [11] While providing unprecedented levels of sensitivity and locating, these systems proved to be prone to a significant level of nuisance alarming and lack of sensitivity at low frequencies. This resulted in poor detection of excavating machinery. In addition, the need for a stable temperature environment for the equipment made it difficult and expensive to operate with consistent and reliable results. It's expensive. A minimum cost for the DVS system is $150,000 USD for a 40km run of cable, plus the need for an expensive temperature-controlled rack to house the system. Any loss of control of temperature, or hard physical contact with the cable, will destabilize the polarization of the light, thus rendering the locating part of the system highly unreliable. It is limited in frequency bandwidth, usually to 10-20kHz. However, the leaks of interest for gas occur around 80kHz and oil/water around 40kHz when the leak is small. [12] This kind of detection is at a late-stage leak, heading for catastrophic failure.
2. Coherent-OTDR or Distributed Acoustic Sensor (DAS) technology is a second generation of distributed interferometer that operates in a reflective (Rayleigh backscatter) configuration. [13] [14] The technology has a significantly lower frequency bandwidth, usually up to a maximum range of 1-10kHz. This is a useful frequency range for large, gross movements/acoustics, but it is also where nearly all environmental nuisance alarms are generated. Also, this technology is not capable of early leak detection since gas leaks occur around 80kHz and oil leaks around 40kHz [12], well beyond the 1-10 kHz maximum bandwidth limitations of DAS systems. The cable for this technology needs to be installed quite deeply, otherwise, it will generate many nuisance alarms. In areas of high background noise, i.e., road crossings, highways, near rail lines, populated areas, etc., it will be susceptible to significant nuisance alarming. It is also critical to understand that, since DAS systems are based on an optical time-domain reflectometer (OTDR) architecture, their resolution and frequency bandwidth diminishes significantly and rapidly with distance. For a 1-2km long system, they can achieve 1m locating resolution and 10kHz frequency bandwidth. However, for a 40-50km system, they would achieve 20m locating resolution and only a 1-2kHz bandwidth at best, rendering DAS systems unsuitable for long pipelines and most early leak detection applications.
3. Distributed temperature sensing (DTS) [15] is another fiber optic sensing technology marketed for leak detection in pipelines. DTS technologies measure static or very low-frequency changes in temperature or strain, which is particularly useful for geotechnical applications (ground movement/settling, soil stability/erosion, pipeline deformation, integrity monitoring, etc.) and the indirect detection of leaks by measurement of temperature differentials (via the Joule-Thomson effect). However, this technology cannot be used effectively for TPI nor acoustic (or ultrasonic) detection of leaks. While initially, it appears simple and effective, particularly when an existing fiber-optic communications cable can be used, the correct installation of the sensor to detect leaks could be very difficult and expensive. Its performance, especially the detection time, depends on ground conditions, the correct placement of the optical fiber cable relative to the pipeline, as well as, on the leak dynamics of the pipeline contents. Actually, owing to their complimentary capabilities, DTS and DVS technologies are highly synergistic, rather than competing. The synergy is not so strong with DAS, however, as they both operate in the low frequency domain, so there is no capability or benefit of detecting early-stage, ultrasonic pin-hole leaks. In spite of this, a combined detection system will become more complex and significantly increase the cost.

In conclusion, conventional DVS and DAS technologies have limited frequency bandwidth, which does not allow the direct detection of small (pin-hole) leaks occurring on an operational pipeline. They are expensive to implement and limited to only detecting TPI events and ground movements from major leaks, offering little potential for a combined early TPI warning and leak detection system.

To address the urgent need of the Oil & Gas industry in monitoring pipelines, Fibersonics developed and patented a new generation of fiber optic technology – the technology is named "Long Ranger™". This technology can be very effective in the prevention of oil spills and/or gas explosions due to its unique ability to detect, locate, and classify (ultra-high frequency bandwidth) vibrations caused by physical activity (such as TPI), while simultaneously monitoring for early-stage leaks, along the entire length of the pipeline in real-time.

2. LONG RANGER™ INTRUSION DETECTION SYSTEM

The Long Ranger™ Intrusion Detection System provides an automated pipeline monitoring solution for prevention and corrective control of the most undesirable and dangerous events that can occur to pipelines, such as leaks and spills, as well as tapping and TPI. The Long Ranger™ operates in real-time and should be considered as a preventative monitoring system since it has the potential to detect the early stages of these events without the cable being directly/physically impacted or damaged. The Long Ranger™ systems can also be potentially effective in the detection of dynamic geo-hazard movements caused by landslides, earthquakes or floods, or excavating activity (by equipment or hand) anywhere within the vicinity of a pipeline, and in some cases before the excavating operation.

The Long Ranger™ technology is based on the fact that light waves propagating in a fiber optic cable are extremely sensitive to any movement, vibration, and acoustic-type noise that may be generated in its nearby environment. These disturbances create microscopic stresses or vibrations in the surrounding soil that are mechanically coupled into the buried cable. These forces on the cable in turn generate highly-sensitive optical phase changes within the fibers. The amount of optical phase change is determined by the strength of the disturbance. Amplitude (strength) and frequencies, as well as several other parameters, are detected. Proprietary software is used to interpret and classify these changes to determine if the signal is a true event or standard ambient/environmental conditions. When a security/safety event is detected, an appropriate alarm is triggered and then transmitted to the mapping software (graphical user interface).

The core Long Ranger™ technology acts as a continuous microphone designed to "monitor" over a quasi-DC to

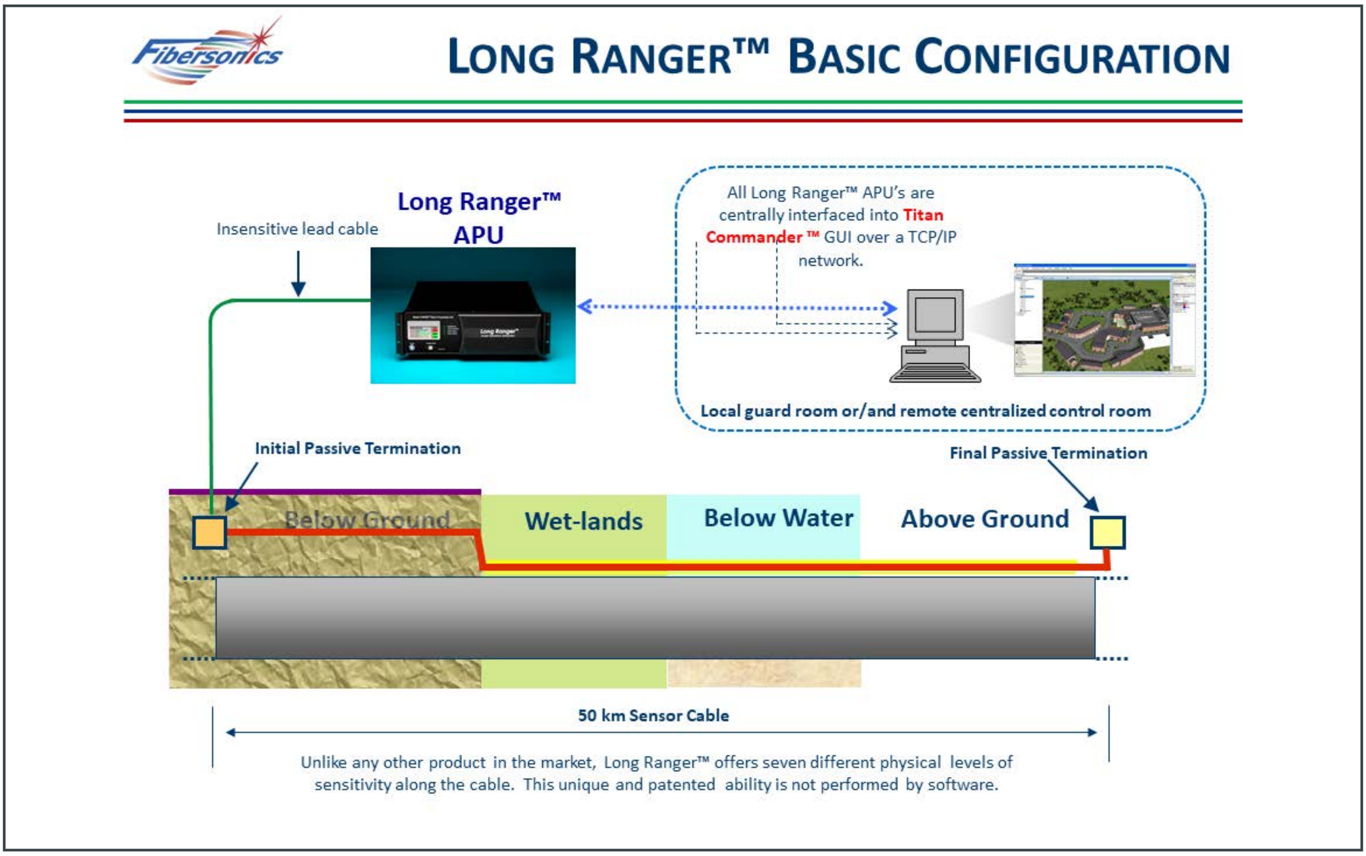

Figure 1: Long Ranger™ System Configuration.

500kHz bandwidth, to very distinctive frequencies generated by TPI and leak events, while discriminating between normal and ambient conditions. TPI events occur largely in the low-frequency range of quasi-DC to 2kHz. Leaks of interest occur around 80kHz for gas pipelines and around 40kHz for oil/water pipelines, when the leak is small (pinhole leak). [12] As the hole increases in size, the frequency lowers to a point where audible sound is made and physical vibrations can be felt.

All other currently available fiber optic-based technologies are limited to a 10-20kHz range, which makes it impossible to detect early, small leaks of pipelines. The Long Ranger™ technology, with its 500kHz bandwidth, is uniquely designed for early leak detection (before audible sounds and physical vibrations are generated). This is by far the widest frequency bandwidth available for any distributed fiber optic sensing technology and is the world's first distributed fiber optic ultrasonic sensor. Consequently, this technology is capable of monitoring far beyond the normal frequency bandwidth of conventional DVS or DAS systems.

Another significant differentiating advantage of this transmissive, hybrid interferometer technology is that its frequency response and location resolution/accuracy are not degraded with increasing distance, unlike conventional DAS systems.

The system consists of an optical fiber cable installed in close proximity, above or near the pipeline, and a dedicated, custom-built controller installed near the pipeline section to be monitored. The controller consists of ultra-high-speed FPGA and DSP microprocessors, electro-optical hardware, and signal processing firmware. The system can be remotely monitored via Fibersonics' Command and Control software Titan Commander™.

Incorporating the Long Ranger™ system into a pipeline's operational control center can provide automated pipeline safety monitoring. The system is designed to quickly and accurately detect and locate any anomaly or breach on the system at any point over the entire length of a pipeline and its networks, enabling the ability to include automation feedback to the SCADA system. The basic system configuration is shown in Figure 1.

For long-haul pipeline applications, additional controllers can be placed every 100km of cable, usually coinciding with compression or pump stations along the pipeline, as shown in Figure 2.

Due to a higher signal to noise (SNR) and a continuous-wave (CW) laser signal, the system can process detected signals at very high speeds, without the need for signal averaging or the need to wait for pulses or echoes to disappear (inherent in DTS and DAS systems). It takes only 10ms for an event to be processed. Furthermore, the system can detect a large number of multi-target dynamic events at the same time.

With the use of high-performance and high-speed device processing, the sensor has a very wide frequency response range from 3Hz to 500kHz, covering the spectrum range of all incidents of interest, including TPI, pigging, leaks,

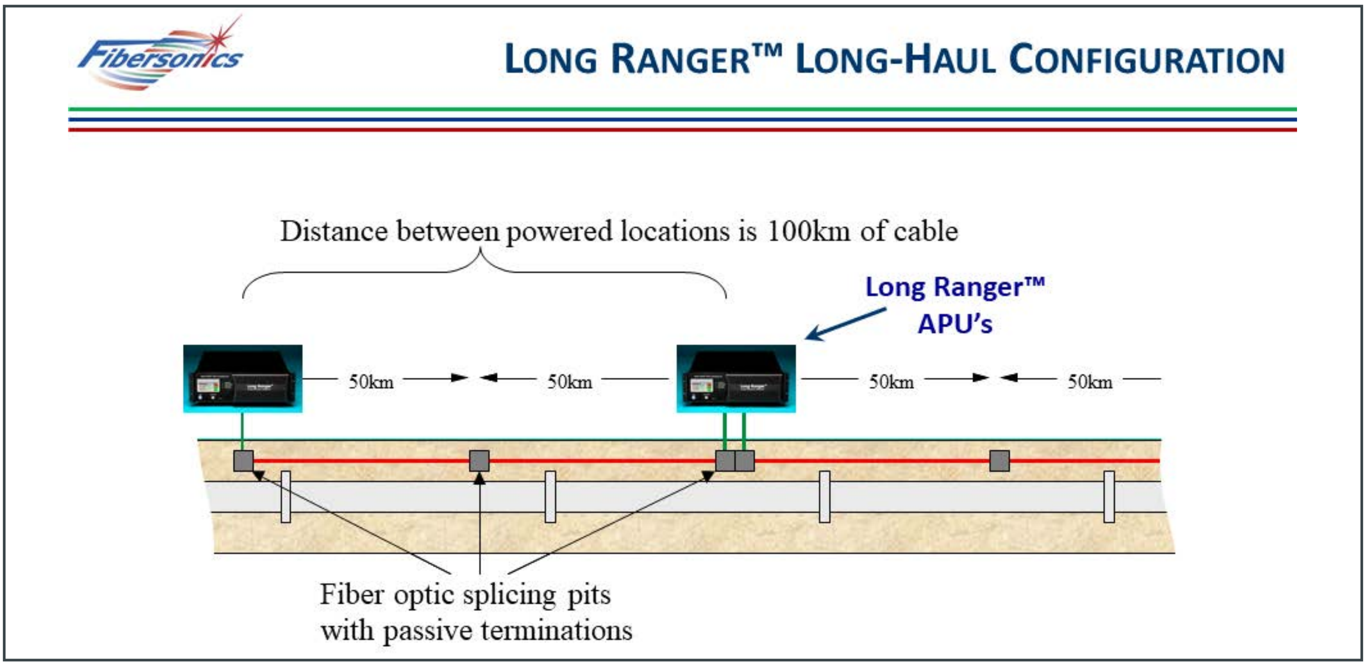

Figure 2: Long Ranger™ Long-Haul Configuration.

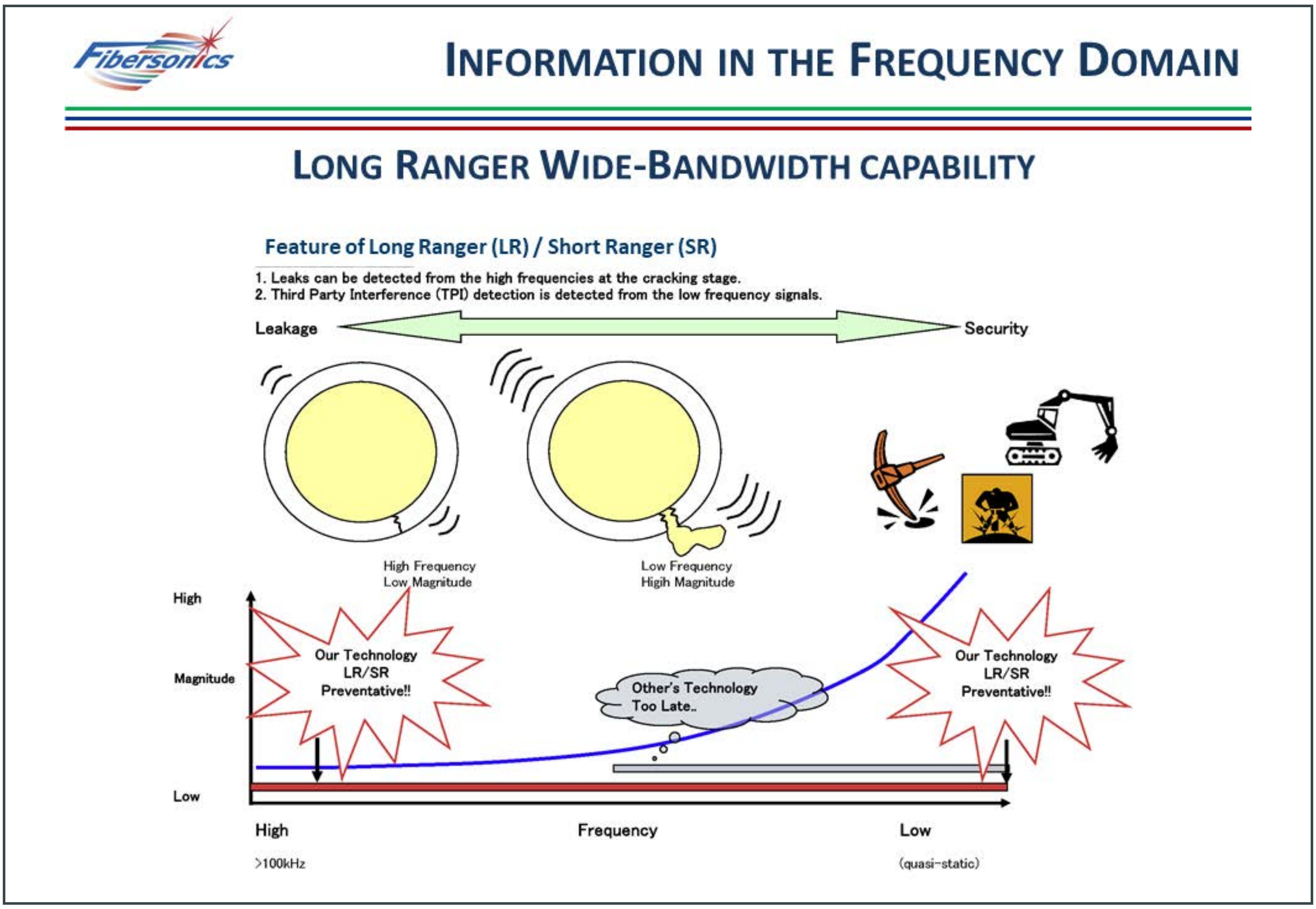

Figure 3: Incidents of interest in the Frequency Domain.

blockages, and pipeline displacement. Figure 3 illustrates the relevance of the ultra-wide frequency bandwidth to incidents of interest.

A multi-parameter, behavior pattern analysis method is used to analyze the signals of various events, including leaking, TPI, pigging, and blockages. It can effectively identify and locate the various types of events of interest while reducing the nuisance alarm rate. Many companies with distributed fiber optic sensing products claim to have developed intelligent databases of event "signatures" that they detect and classify alarms from. However, because so many uncontrolled project/site factors impact on the characteristics of a signal (ie., soil type, rock content, moisture content, temperature, distance from cable, cable design, etc.), we believe their method is unreliable since the signatures will be different from site to site.

Fibersonics has developed a different method for event classification. The proprietary methodology, known as the Unified Algorithms (UA), are a structured, layered approach to event classification and alarming, consisting of algorithms that look at staged data sequentially, applying user-defined parameters and algorithms that maximize the probability of detection (PD) while minimizing the nuisance alarm rate (NAR). We are having great success with this approach. Table (1) illustrates how factors are interrelated in the behavior pattern analysis.

3. VALIDATION OF THE CORE TECHNOLOGY

The core Long Ranger™ technology was developed between the years of 2010-2014. During the years of 2013-2016, the system underwent considerable independent field testing and validation on a number of test and operational pipelines. The system has also undergone independent testing in a Joint Industry Program (JIP) leak detection program. Figures (4) to (9) illustrate some of the results from the independent studies.

In Figure 5, the 0.125in orifice leak is seen at a frequency of 30kHz for a pipeline pressure of 119psi. As shown in Figure (6), when the pressure was increased to 558psi, the detected frequency increased to approximately 120kHz. At 1,063psi, the detected frequency increased to approximately 230kHz. All of these ultra-high frequencies are impossible to detect without an ultrasonic capability.

Events	Amplitude	Energy	Duration	Repetition	Frequency	Location
Hand tools	*	*	*	*	*	**
Backhoe	***	***	**	**	**	***
HDD	**	**	***	***	*	**
Blockage	**	**	***	***	**	***
Leak	*	**	***	***	***	**
Pipe Displacement	*	**	***	**	*	**
...	...	...	...	...	...	...

Table 1: Multi-parameter, behavior pattern analysis.

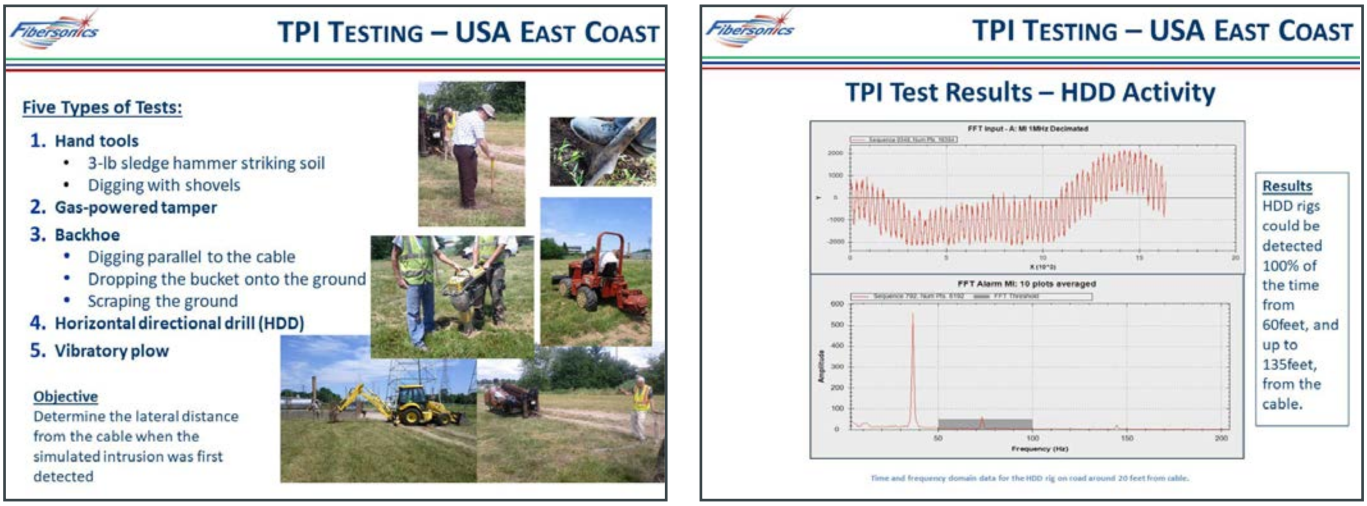

Figure 4: Independent TPI Validation in 2013 with Northeast Gas Association, NYSearch [16]. Various types of equipment were tested. Result shown is for HDD detection.

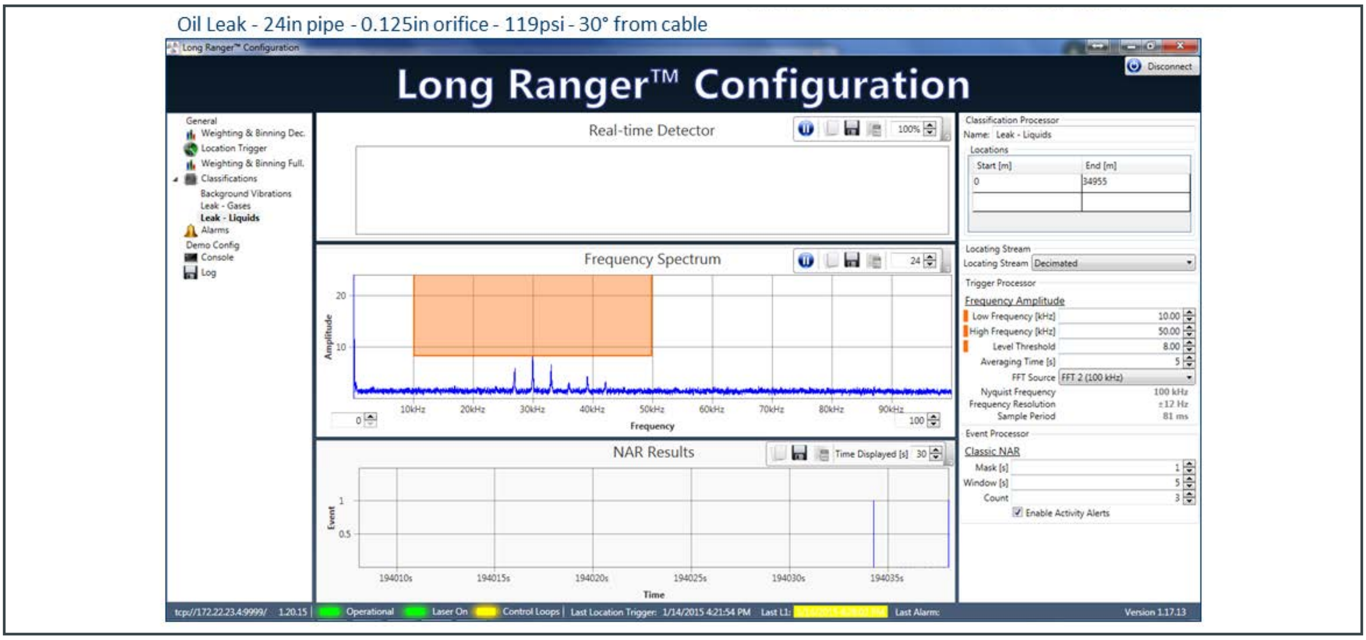

Figure 5: Result from Independent JIP Leak Study in 2015.

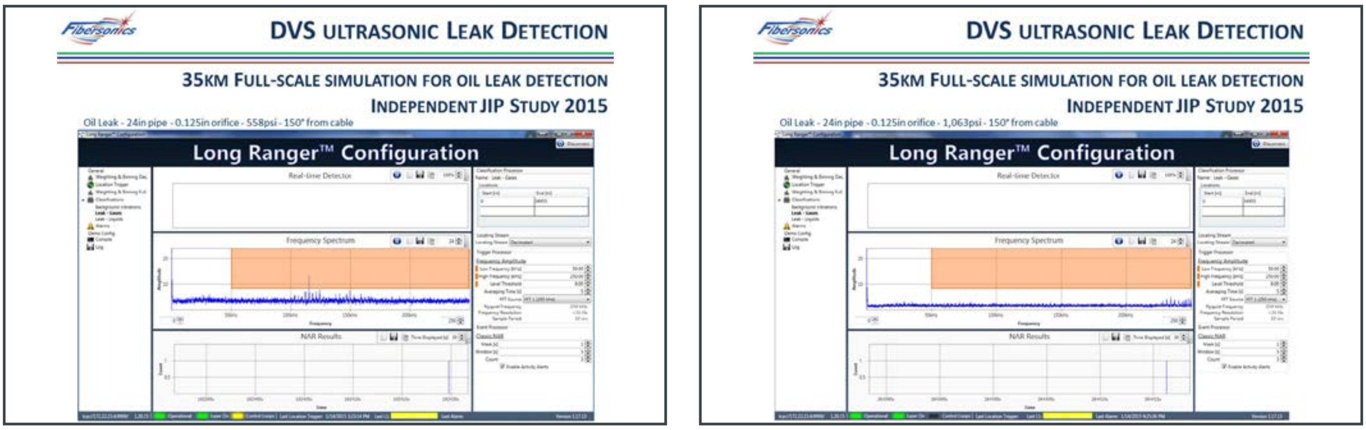

Figure 6: Results from Independent JIP Leak Study in 2015 at higher pressure.

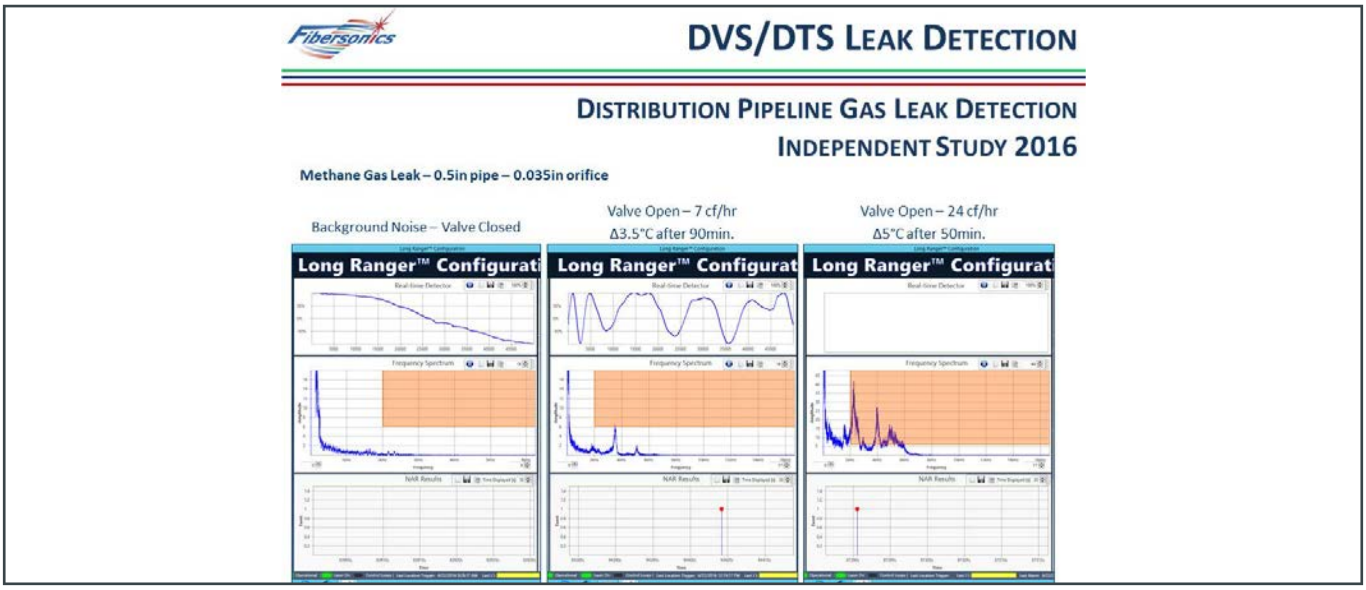

Figure 7: Result from Independent Leak Validation in 2016.

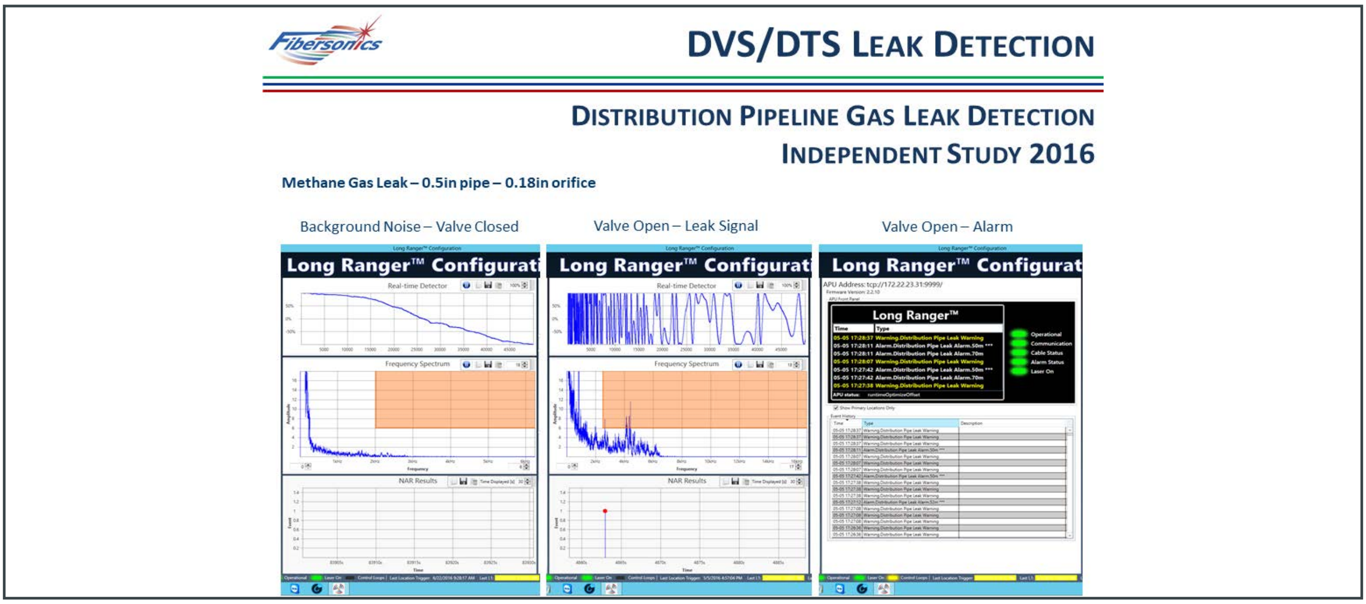

Figure 8: Result from Independent Leak Validation in 2016.

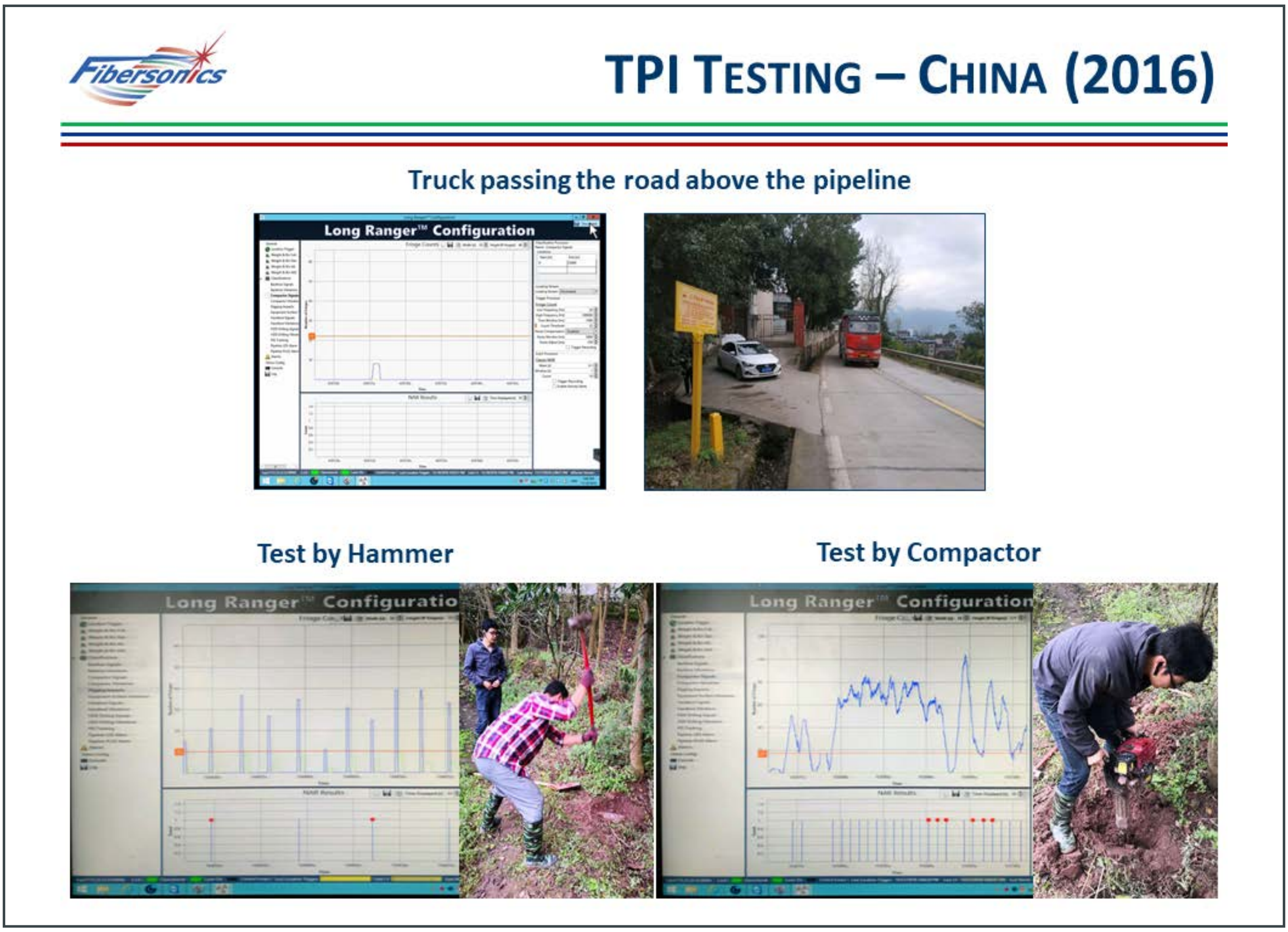

Figure 9: Result from independent TPI Validation in P.R. China in 2016.

4. PROJECT EXPERIENCE IN P.R. CHINA

Since the launch of Long Ranger™ solution in 2015, dozens of successful projects have been implemented around the world, including in the United States, South America, the Middle East, Europe, Asia, and P.R. of China. In 2014, the P.R. China made a commitment to invest significantly in this area. [17] To date, we have provided operators in the P.R. China with a complete set of pipeline leakage and safety early warning solutions. This opportunity has enabled us to obtain considerable amounts of field data and experience in different environments and field conditions. We would like to share some of our experience, as follows.

CASE NO.1, IN THE NORTH OF P.R.CHINA:

Pipeline conditions: gas, diameter 1,016mm, working pressure 5MPa, buried depth 1.5-2m. Geological conditions: flat area, clay, and sandy soil, the water content of soil 15%. Fiber cable: communications cable, loose tube, 12 cores, buried 0.5-2m to the side of the pipeline.

There are a lot of peaks in the displayed screenshot. The peaks have a narrow width, low amplitude, and appear at intervals. Each peak represents one digging activity. It fits logically with the action characteristics of manual digging activities.

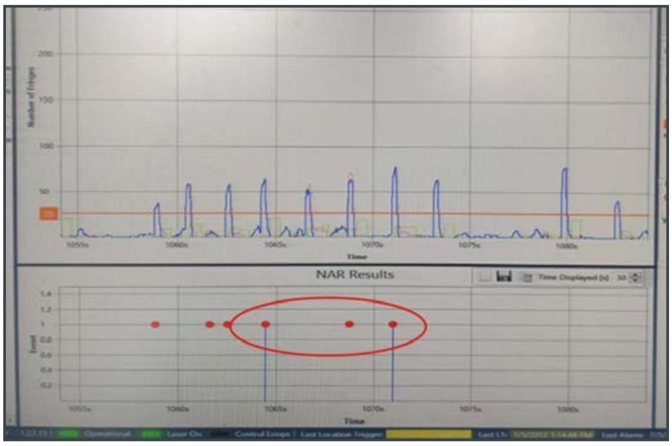

Figure 10: Hand tools activity.

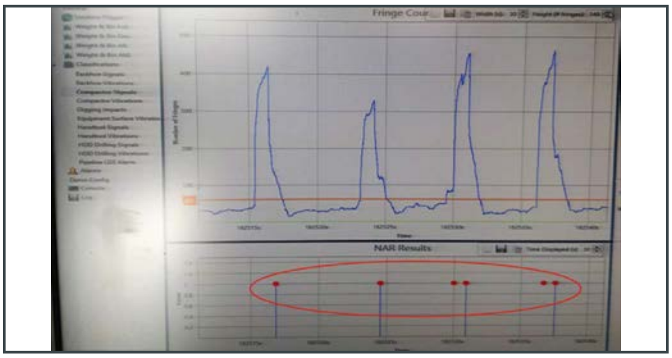

Figure 11: Backhoe activity

The peaks in the displayed screenshot have a wider (time) width, higher amplitude, and longer gaps compared with Figure 10. There is an alarm at each peak. It fits logically with the action characteristics of backhoe digging activities.

Mechanical activities are shown in the following figures.

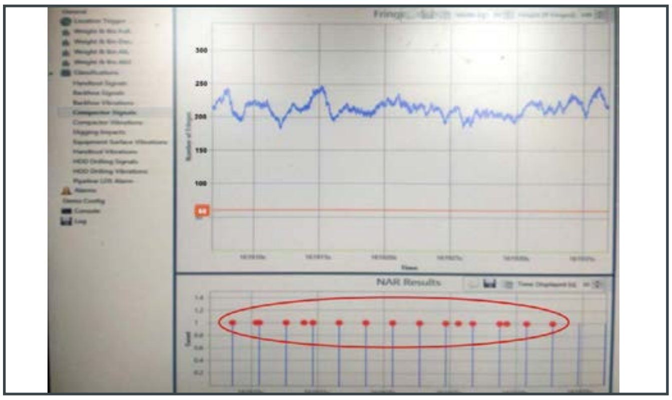

Figure 12: Rock drill

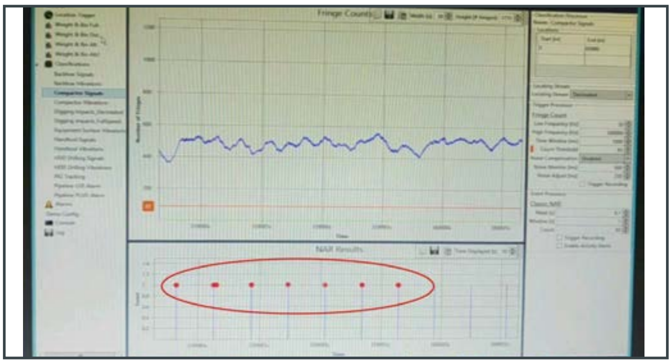

Figure 13: HDD Activity

Figures 12 and 13 illustrate a different kind of response. There are no transient peaks in the signals since these represent and are detected as continuous signals. Also, the amplitude of the continuous signal is high, meaning it is a strong and constant activity. Accordingly, the alarms occur continuously. This is a typical signal generated by a rotating type of machine, operating at constant high speed. As can be seen, they have similar waveforms. However, the difference between them can be seen clearly in the frequency content of their signals, as they rotate at different speeds.

CASE NO.2, IN THE NORTH OF P.R.CHINA:

Pipeline conditions: gas, diameter 1,016mm, working pressure 6MPa, buried depth 1.5-2m. Geological conditions: flat area, clay, and sandy soil, the water content of soil 15%. Fiber cable: communications cable, loose tube, 24 cores, buried 0.5-2m to the side of the pipeline.

a) Air Compressor operating on the pipeline:

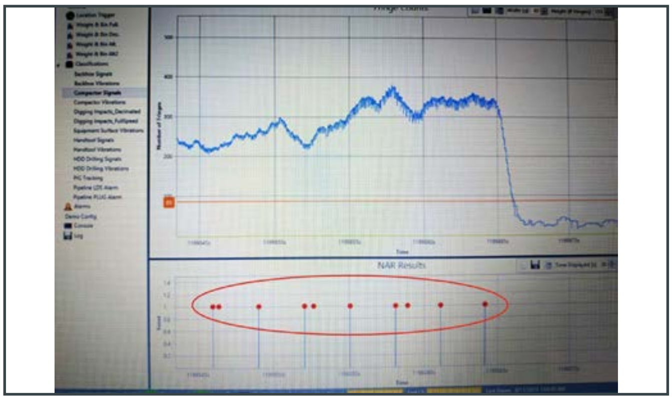

Figure 14: The acoustic echo.

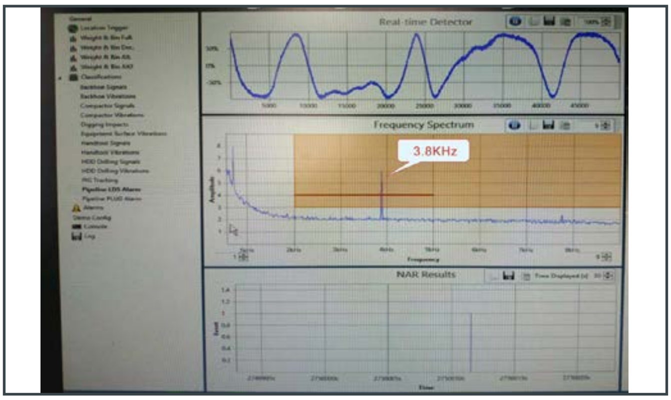

Figure 15: The frequency spectrum

Figure 14 illustrates the signal generated by the internal acoustic echo of the air compressor. Figure 15 displays the frequency spectrum of the signal. In Figure 14, the signal can be seen to be strong (high amplitude) and continuous. Also, the alarms occur continuously. It is clear that the signal suddenly drops, representing that the air compressor operation was stopped after reaching the predetermined pressure. Figure 15 illustrates the corresponding frequency spectrum, clearly showing a strong vibration frequency during operation of 3.8kHz. In this scenario, the system can be programmed to not alarm on such types of signal/event characteristics, if desired.

b) Pipeline maintenance:

Maintenance work is often carried out in the pipeline operation. Often, personnel use grinding equipment at the pipeline weld joints. Figure 16 further below displays a site photo of such a scenario. Figure 17 illustrates the signals and alarms generated in the Long Ranger™ system during this maintenance operation. There are two very large peaks seen in Figure 17, each peak has a wide width and a vibratory type of oscillation is evident riding on the main signal peaks. There is also a long interval between the two peaks. Figure 17 shows the operating characteristics of the grinding equipment operated by the maintenance personnel.

Figure 16: Site Maintenance

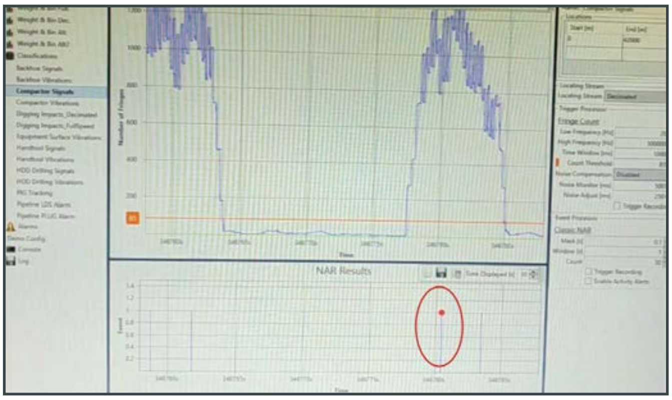

Figure 17: Grinding Signals

c) Pipeline displacement:

On one occasion, a very strange type of signal was detected, as illustrated below in Figure 18. As you can be seen, the signal waveform is continuous and wavy, with relatively large amplitude but very low frequency. By measurement, the frequency is approximately 10Hz. This alarm activity lasted about two minutes at position 5km. After physically checking at the position of the alarm, at the corresponding position on the pipeline, we found that there was several tons of construction rubbish that had been dumped directly on top of the pipeline. Also, fresh truck tire tracks were found at the site. This confirmed that the alarm was caused by the ground/pipe deformation caused by the pressure of a heavy object placed over the pipeline. When the trucks were unloading the rubbish, the weight of the rubbish fell slowly, producing continuous pressure on the ground, due to which the pipeline experienced a weak elastic displacement. However, when the dumping process was completed, the pipe returned to its normal position.

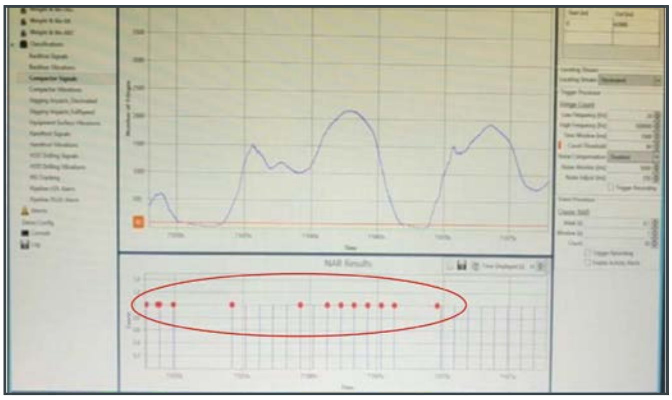

Figure 18: Pipeline displacement signal.

The whole process lasted only about 2 minutes and was detected by the sensor completely. This signal characteristic is highly consistent with the above events.

CASE NO.3, IN THE NORTH OF P.R.CHINA:

Pipeline conditions: gas, diameter 1,219mm, working pressure 8MPa, buried depth 4m. Geological conditions: hilly area, sandy soil, the water content of soil 10%. Fiber cable: communications cable, loose tube, 24 cores, cable in conduit, buried at 5 o'clock position 0.5m from the pipe.

a) Blockage in the pipeline:

Sometimes, ice blockages (plugs) occur in the oil and gas pipeline during operation. When the blockage occurs, the inner diameter of the pipe effectively becomes smaller and the local gas velocity increases at the blockage area. Under the influence of the high pressure, it causes the vibration (like a turbulence noise) of the pipeline. The vibration signals leak out through the metal tube wall and are detected by the optical fiber cable, generating alarms by the system. Figures 19 to 22 illustrate the system response to one such incident that was detected.

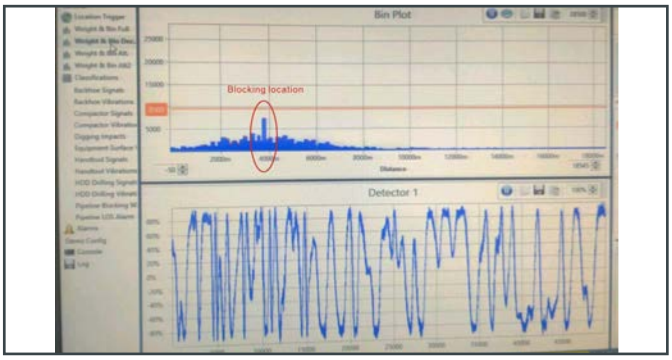

Figure 19: Blockage signal (before treatment).

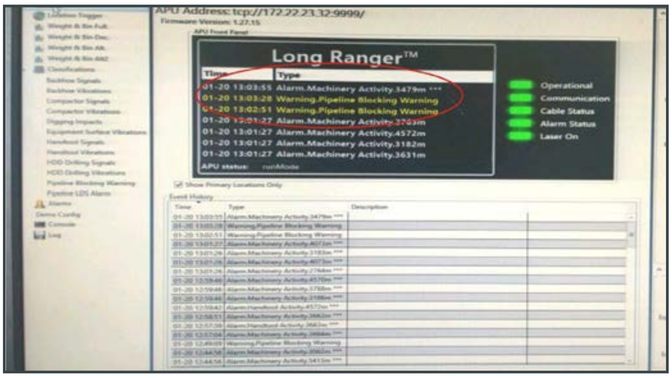

Figure 20: Blockage alarm and location

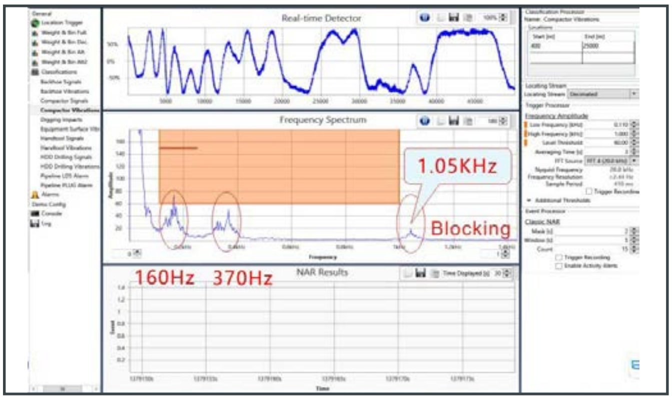

Figure 21: The blockage spectrum.

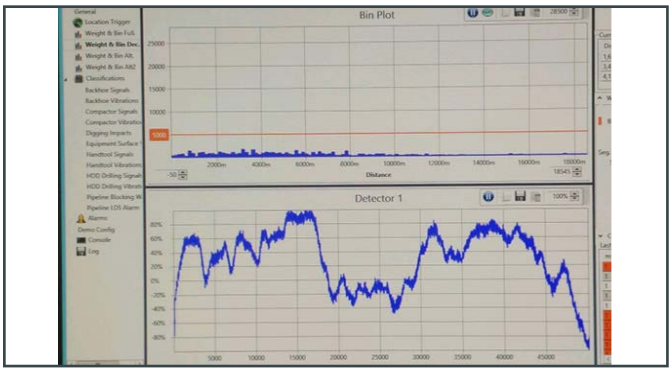

Figure 22: The blockage cleared (after treatment).

Figure 19 illustrates that the maximum amplitude is located at the center of the pipe blockage area, at position 3,479m, and spreads to the both sides for thousands of meters. By analyzing the spectrum of Figure 21, the vibration signals have three frequency components. The component at 160Hz is background noise, 370Hz is the friction signal between the gas and pipeline and 1.05kHz is the high-frequency vibration signal caused by the blockage (plug) in the pipeline. With the increase of blockage, the inner diameter of the pipe and the vibration frequency will both change. The more blockage, the higher the frequency of the vibration. By observing the changes, the development trend of the pipeline blockage can be monitored in real-time, while providing technical support for maintenance and emergency teams.

When this activity was first detected and alarmed by the Long Ranger™ system, a 30m long trench was carefully dug over the pipeline at the determined location of 3,479m. When the depth of the ditch reached about 2m, the personnel in the trench found that the ground under their feet was trembling distinctly. Once the pipeline was exposed, it was possible for them to feel a strong vibration on the pipeline surface.

The position with the maximum vibration was determined to be the location of the blockage, and this position was only 10m from where the Long Ranger™ system had alarmed. Afterward, with the continuous injection of methanol into the pipeline, the development trend of the pipeline blockage was monitored continuously using the Long Ranger™ system. After 72 hours, the system showed that the pipeline blockage became significantly weaker, as illustrated in Figure 22. The operator of the pipeline was impressed with the performance of the system, which had saved them countless hours and cost in this scenario.

b) Leaking detection:

With long-distance pipelines, normally, there is a pressure station along the line every certain distance, which has a relief port inside. When the pressure in the line exceeds a certain limitation, the relief port can be opened to reduce the pressure in the main pipeline. The relief port is connected to the main pipeline by a smaller diameter pipe. When the discharge occurs, the discharged gas will produce friction with the nozzle and the air, causing a high frequency (turbulent) vibration. The vibration frequency is so high that only a high-frequency hissing can be heard by humans. Sometimes, the frequency is even too high for humans to hear. The Long Ranger™ system, however, can detect the vibration easily thanks to its ultrasonic frequency bandwidth and then generate alarms, if desired. One such scenario was detected during the blockage event that was described above. The system detected the discharge several times, even though the port was located 150m away from the main pipeline. Figure 23 illustrates the discharge signal and frequency spectrum. The discharge vibration frequency was at 42.4kHz.

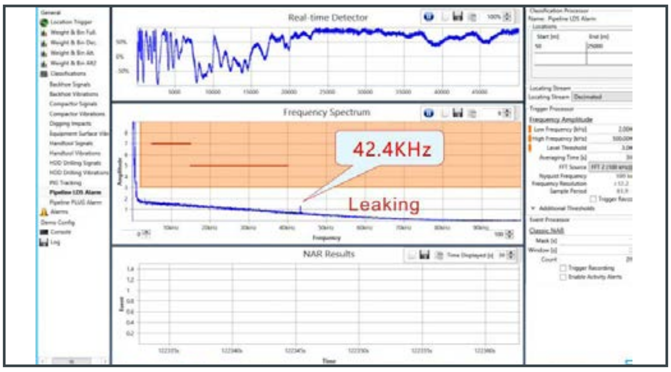

Figure 23: Discharge frequency spectrum.

5. SUMMARY

The Long Ranger™ technology and system have been briefly presented. It is distinguished by the following main operational capabilities:

1. It operates over an extremely broad frequency range (3Hz to 500kHz) and is the world's first and only distributed ultrasonic detector. As a result, it can detect and locate many difficult or complex types of signals, directly and much earlier than other cable-based systems.
2. It is effective at discriminating different patterns of interferences and environmental/traffic noises from potentially dangerous operational events/threats. By reducing nuisance alarms, it alarms for events of true concern with an increased degree of confidence and thus allows for automatic response mechanisms with a practical degree of responsibility.
3. It offers completely uniform sensitivity and performance over the entire length of the optical fiber cable. Most other systems are non-uniform and their performance diminishes with distance.

This technology can be very effective in the prevention of oil spills and/or gas explosions due to its unique ability to utilize an ordinary optical fiber cable to both detect, locate and classify vibrations caused by physical activity (such as TPI), while simultaneously monitoring for early-stage leaks, along the entire length of the pipeline in real-time.

References

1. P. Hopkins, „Learning from Pipeline Failures," in WTIA/APIA Welded Pipeline Symposium, Perth, Australia, 2008.
2. M. Cech, P. Davis, F. Gambardella, A. Haskamp and I. Huidobro Barrio, „Performance of European cross-country oil pipelines," Concawe Report 12/20, Brussels, 2020.
3. Alberta Energy and Utilities Board, „Report 2007-A: Pipeline Performance in Alberta, 1990-2005," 2007.
4. S. Asadollahi, A. Dorée, L. olde Scholtenhuis and F. Vahdatikhaki, „Review of Detection and Monitoring Systems for Buried High Pressure Pipelines," 2017.
5. X. Bao and L. Chen, „Recent Progress in Distributed Fiber Optic Sensors," Sensors, vol. 12, no. 7, pp. 8601-8639, 2012.
6. M. Fernandez, E. Tapanes and P. Zelitskaya, „Pipeline Hydrocarbon Transportation: Some Operating Concerns and R&D Trends," in ASME Internation Pipeline Conference 1996 (IPC ,96), Calgary, Alberta, Canada, 1996.
7. E. Tapanes, M. Fernandez, P. Zelitskaya, J. Beckman and A. Gilroy-Scott, „Fibre Optics Sensor Technology for Pipeline Applications," in ASME International Pipeline Conference 1996 (IPC ,96), Calgary, 1996.
8. E. Tapanes, „Dual-Purpose Fibre Optic System Providing Simultaneous, Real-Time Communications and Distributed Vibration Sensing for Pipelines," in ASME International Pipeline Conference 1998 (IPC ,98), Calgary, Alberta, Canada, 1998.
9. E. Tapanes, „Fibre Optic Sensing Solutions for Real-Time Pipeline Integrity Monitoring," in Australian Pipeline Industry Association National Conevtion, Australia, 2001.
10. E. Tapanes, J. Goode and J. Katsifolis, „Apparatus and Method for Monitoring a Structure Using a Counter-Propagating Signal Method for Locating Events". USA Patent 6,621,947B1, 16 September 2003.
11. E. Tapanes, J. Goode and J. Katsifolis, „Apparatus and Method for Montoring a Structure Using a Counter-Propagating Signal Method for Locating Events". USA Patent 6,778,717B2, 17 August 2004.
12. A. Brunner and M. Barbezat, „Acoustic Emission Monitoring of Leaks in Pipes for Transport of Liquid and Gaseous Media: A Model Experiment," Advanced Materials Research, Vols. 13-14, pp. 351-356, 2006.
13. L. Palmieri and L. Schenato, „Distributed Optical Fiber Sensing Based on Rayleigh Scattering," The Open Optics Journal, Vols. 7, (Suppl-1, M7), pp. 104-127, 2013.
14. X. Guo, K. Yong, X. Xueying, L. Yang and G. Ao, „Research Progress of Phase Sensitive Optical Time Domain," International Journal of Research in Engineering and Science (IJRES), vol. Volume 5, no. Issue 6, pp. 62-69, 2017.
15. A. Ukil, H. Braendle and P. Krippner, „Distributed Temperature Sensing: Review of Technology and Applications," IEEE Sensors Journal, vol. 12, no. 5, pp. 885-892, 2012.
16. D. D'Zurko, „NGA NYSEARCH R&D Programs Related to Damage Prevention," in PHMSA R & D Forum, WG #1, 2016.
17. Thomson Reuters, „Sinopec to spend billions to handle oil pipeline safety problems," Thomson Reuters, 2014.

Authors

Edward Tapanes

Fibersonics Inc.

President and CEO

edward@fibersonics.com

Li Xiaotong

Fibersonics Inc.

Country Manager

laury_lee2000@aliyun.com