Rockmass response monitoring in deep mining using DAS and DSS systems distributed

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ABSTRACT

The mining industry is undergoing a technological transformation in the way it collects and utilizes data. One technology leading this change is Distributed Fiber Optic Sensing (DFOS). DFOS technology can tackle the complex issues of mine safety and operational efficiency. It allows for continuous, real-time monitoring of temperature, strain, and seismic activity. Compared to traditional sensing methods, DFOS acquires data with fine spatial and temporal resolutions, thereby enabling advanced monitoring for improved safety and stability of mining operations.

Adoption of this technology encourages mining companies to innovate and improve on traditional data collection practices. Implementing DFOS improves the predictive accuracy for identifying both small- and large-scale geotechnical instabilities. While DFOS complements existing hazard management strategies like Triggered Action Response Plans (TARPs) and "traffic light" warning systems, it can surpass these traditional methods; of rockmass It is straightforward to deploy fiber optics cable in and around the mine's infrastructure at long distances. This enables the DFOS to acquire many data points (as if we have a sensor every meter) and therefore monitoring a large volume with fine resolution.

This paper explores applications of DFOS in mining, through some examples and case studies. It discusses the technology's status, advancements and limitations. Special focus is given to challenges related to block cave monitoring and instrumentation, which are particularly problematic in terms of visibility and data collection. By integrating DFOS into mining operations via existing or specially drilled boreholes, or by instrumenting drifts and shafts, mines can enhance their monitoring and decision-making capabilities.

1 ROCKMASS RESPONSE MONITORING USING DFOS

Rockmass response monitoring using Distributed Fiber Optics Sensing (DFOS) technology has been used in underground mines over the past few years with potential to become a primary platform for continuously assessing the state of the rockmass, allowing proactive decisions (Furlong & Anderson 2022). The system typically comprises Distributed Acoustic Sensing (DAS) and/or Distributed Strain Sensing (DSS) technology and can monitor for multiple parameters such as low frequency changes in strain (often referred to as "slow strain"), absolute strain and microseismic monitoring and imaging. DFOS technology has a long provenance. DSS (Parker et al, 1997) and DTS (Farhadiroushan, et al, 1997) have been operating commercially from the 1990's and DAS from a decade later. DFOS has been applied and is rapidly evolving in other industries such as alternative energy (Binder & Abatchev 2021), environmental and earth sciences (Hudson et al. 2021), infrastructure (Monsberger & Lienhart 2021), carbon capture and utilisation (Hopkins et al. 2021), oil and gas (Jin & Roy 2017), and mining (Alkhaffaf, S, et al. 2022, Riedel et al. 2018; Bellefleur et al. 2018). In mining applications, DFOS has been used for seepage and structural integrity

monitoring of tailings storage facilities, (Johanson, S, 2017, Alkhaffaf, S, 2022), Flow metering, (Amir & Anderson 2022), and VSP surveys for exploration (Riedel et al. 2018) among other applications such as high preconditioning in high-stress rockmass and conveyor belt monitoring.

1.1 How DFOS technology works

When transmitting data through optical fibers, light experiences attenuation via absorption and scattering along its length. Distributed sensing utilizes different types of fiber interrogators to assess scattering interactions, such as Rayleigh, Brillouin, and Raman scattering, and quantify parameters such as temperature, acoustics, or strain along the entire length of fiber optics cable, Figure 1.

Brillouin and Raman backscattering can be used to measure strain and temperature to 1 micro-strain and 0.01°C levels of resolution respectively. Typically, DSS and Distributed Temperature Sensing (DTS) systems are used to measure Brillouin and Raman backscatter signals.
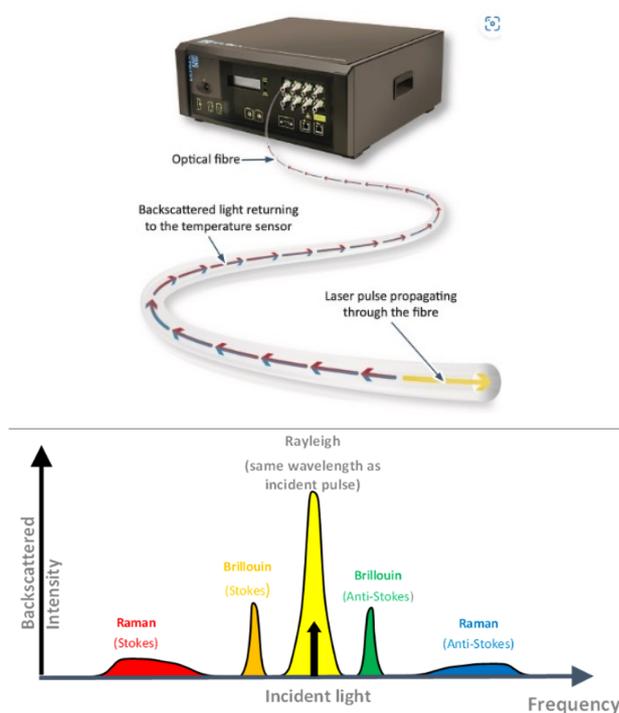

Figure 1   **Principals of DFOS technology, showing the interrogator (Top) and types of backscatter light (Bottom).**

The DAS system measures both acoustics and dynamic strain signals through Rayleigh backscattering with a high level of accuracy. DAS units that are phase coherent, can measure the true acoustic wave, (Parker, et al, 2014).

The technology is specifically advantageous for monitoring large volumes at high resolution, since it is possible to deploy fiber for many kilometers within the monitoring object and acquire measurements (of temperature, strain and acoustic simultaneously) typically at every meter along the fiber cable. This compared to traditional sensors, such as piezometers, extensometers or geophones can provide hundreds of additional measurement points and a more detailed insight into the changes within the infrastructure being monitored. Figure 2 shows temperature measurements at a dam along 500 meters of fiber optics cable and areas of anomalies, indicating temperature distress and seepage.
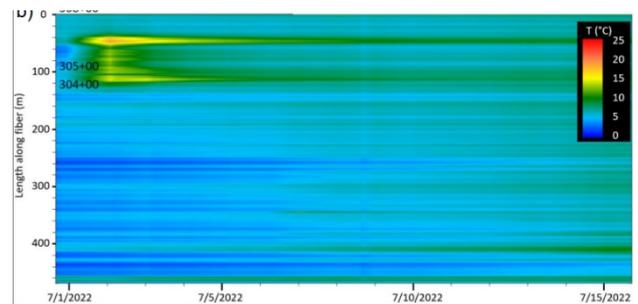

Figure 2   **Temperature map along 500 m fiber optic line at a Dam for seepage monitoring, (Wagner, 2023).**

1.2 The applications of DAS/DSS systems in block caving and underground mining

DAS and Carina Sensing Systems represent advanced developments in Fiber optic sensing technology. The DAS interrogator can operate at a repetition rate of up to 100kHz, measuring changes in the Rayleigh backscattered light signal. This measurement allows for the determination of strain changes at each sampling point along the fiber.

1.2.1 DAS for seismic and microseismic applications

Increasing stress conditions in deep underground mines induce higher rates of microseismic activity and larger magnitude events. Furthermore, the change in stress level, due to accumulated extraction, contribute to a longer seismic decay period after a large-magnitude event (Vallejos & McKinnon 2009). Monitoring microseismicity in deep mines has now become a standard practice in many mining regions of the world.
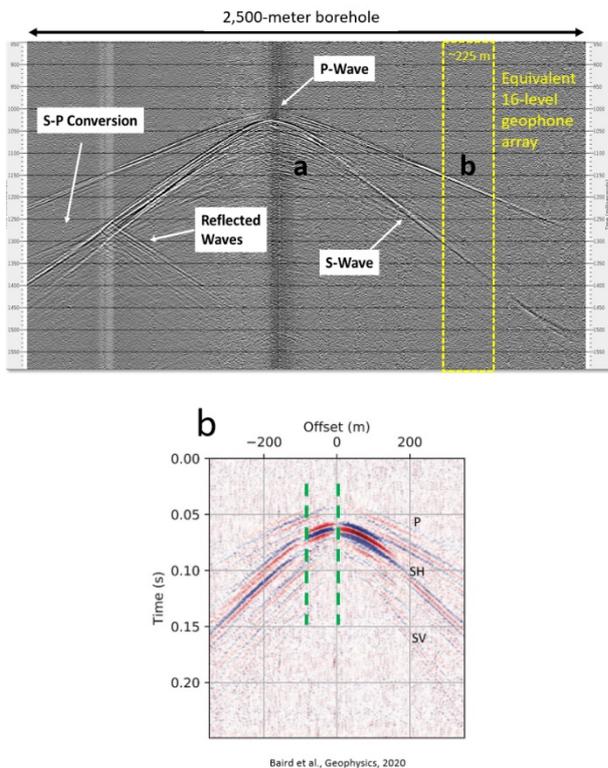

Figure 3 **Sample microseismic event recorded on a DAS array (a) capturing p-wave, s-wave, reflected waves, and S-P conversion. A comparable 16-level geophones array would capture significantly less signal fidelity. Example DAS recording showing polarity (b) of an event with clear P, SH, and SV arrivals, with polarity reversals observed in the SH and P (from Baird et al. 2020).**

DAS turns the standard fiber optics cable into a series of acoustic sensors equivalent to hundreds of uniaxial geophones, where it captures amplitude, frequency, and phase at each point along fiber. A sample microseismic event arrival over a 2.5km borehole is shown in Figure 3 where a dense array of acoustic spatial sampling is acquired on fiber using DAS. This is a significant advantage in mining applications, where velocity models are often heterogenous and comprise varying rock types and geological structures and therefore varying seismic velocities.
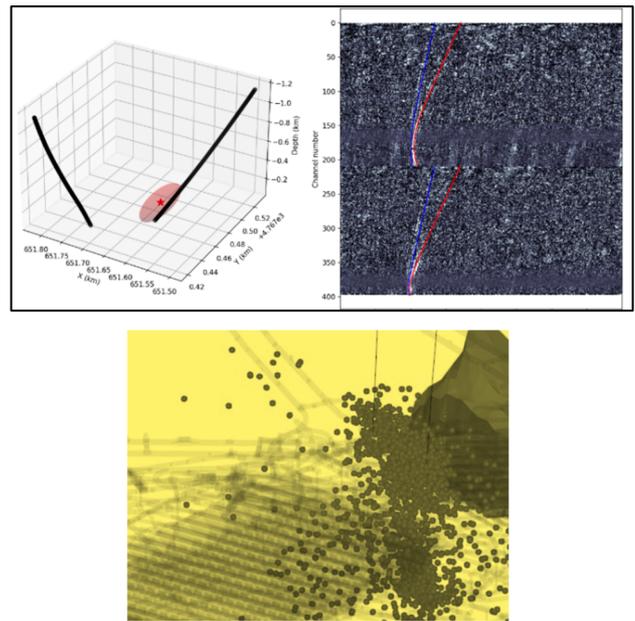

Figure 4 **A seismic event located on a DAS system and two fiber-instrumented boreholes (Top), a cluster of seismic events located by a DAS system at a mine operation (Bottom).**

DAS provides a denser sampling, increasing hypocenter location accuracy through the generation of more ray paths and therefore minimizing the effects of velocity ambiguity. Moreover, further spatial sampling of the propagating wavefield is expected to add additional accuracy to moment tensor inversions. In some DAS recordings, the focal sphere transition is readily seen in the seismic recordings. Finally, tomographic imaging of the subsurface benefits from additional ray paths to increase the accuracy of subsurface models, (Furlong 2021). Figure 4 shows examples of seismic events acquired by DAS systems at mines.
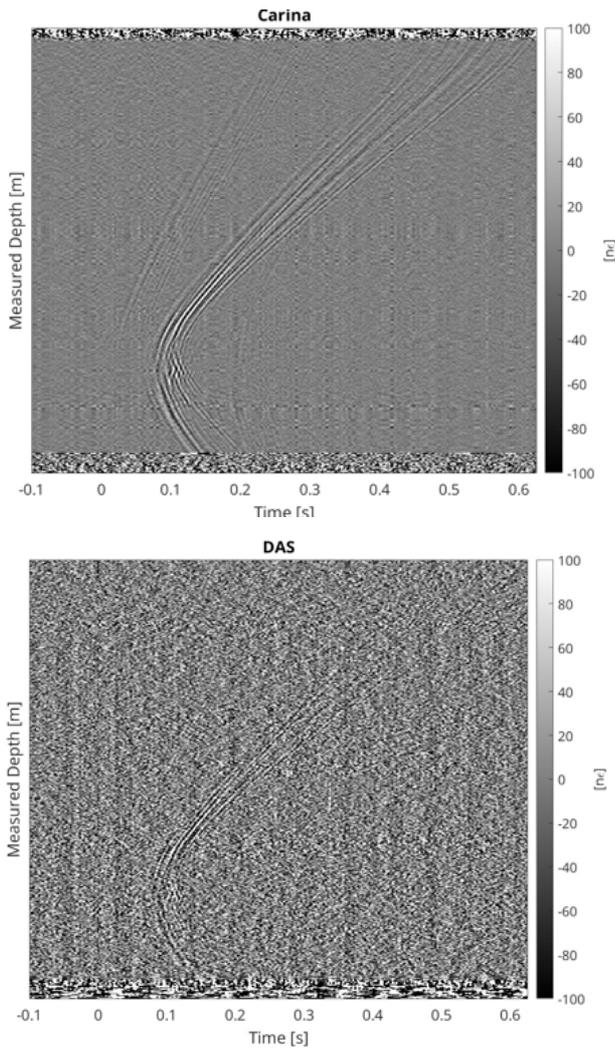
Figure 5 **Comparison of acoustic signals and noise level between a Carina (Top) and DAS (Bottom).**

In DAS applications, the frequency range varies from a few millihertz to over 50kHz which can provide an advantage over geophone-based systems, where a range of small to large magnitude events can be detected using a single DAS system. in a recent block cave monitoring application, this capability has allowed the detection and location of small magnitude microseismic clusters that map the seismogenic zone and cave profile in more detail. This study is expected to be published in 2025.

It should be noted that DAS measures strain rate only along the axis of fiber and therefore is equivalent to a uniaxial geophone.

1.2.2 Carina DAS and Constellation Fiber

Using DAS for microseismic applications poses a challenge due to the fiber's sensitivity to weak incoming wavefields that may not exceed the system's noise floor. To enhance performance, an engineered optical fiber can be used for monitoring. Some Constellation fibers in conjunction with enhanced DAS systems such as Carina, offer a 20 dB signal response enhancement, resulting in a total dynamic range of 130 dB, (Richter, P, 2019). The Carina system returns 100 times more light than standard fibers with minimal additional optical loss, Figure 5. The system's design aligns the periodicity of the scatter centers in the Constellation fiber with the gauge length of the Carina interrogator. This synchronization significantly lowers the system's noise floor, unveiling previously obscured optical signal details. The Carina system, with its enhanced capabilities, has gained prominence in various industries, often replacing traditional geophones in microseismic applications, particularly in oilfield operations.
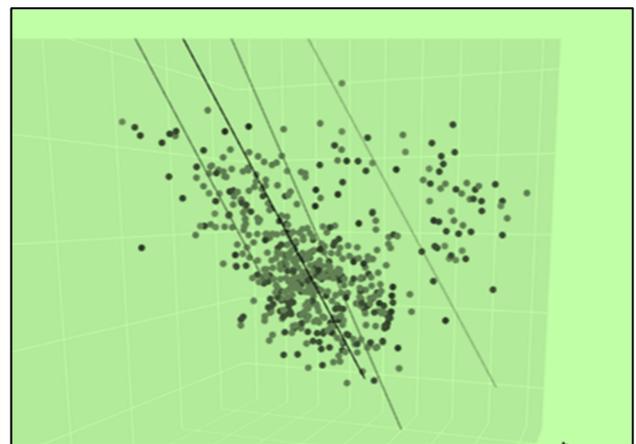

Figure 6 **A rockmass preconditioning program run from short boreholes drilled within the mine. A small subset of the total recorded events is shown.**

DAS is also specifically suited for monitoring of hydraulic fracturing applications to precondition the rockmass. A subsection of microseismic events is shown in Figure 6 for a subsurface preconditioning program. Preconditioning programs are becoming more common as they are projected to reduce the risk of large-magnitude events and mitigate the rock burst

hazard in mines. Equipping existing boreholes with fiber would allow the hydraulic precondition program to be mapped similarly to how microseismic is mapped for oilfield fracturing operations. Fracture dimensions determined from microseismic will help evaluate the total stimulated rock volume and the general efficacy of the program.

There are inherent limitations and challenges with DAS that need to be addressed. DAS is most sensitive to strain along the fiber axis and least sensitive to orthogonal strain. Although DAS arrays are designed to be insensitive to primary waves arriving orthogonally, slight deviations from 90 degrees can still produce a detectable signal. Determining event magnitudes is also more complex with DAS, as it records strain rates rather than velocity. Converting DAS responses to displacement requires careful consideration, but studies have shown a strong correlation between DAS and geophone-calculated magnitudes, Figure 7.
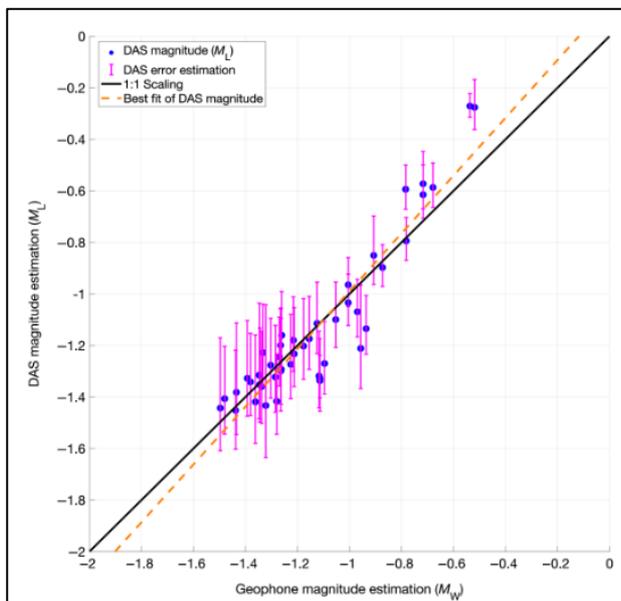

Figure 7 Seismic magnitude correlation between DAS and geophone data. Lellouch et al., 2020.

1.2.3 DAS and DSS for strain measurements

The same DAS and fiber optics cable used for acoustics measurements, can also be used for strain measurements. DAS interrogators allow for dynamic strain measurements with their ability to measure very low frequencies. While

geophones signal becomes aliased below ~10-15Hz, DAS has a flat system response to near DC, meaning it can maintain accurate measurements below 0.1Hz. DAS has been tested for the measurement of insitu stress in the rockmass using inversion algorithms, (Ohanian, 2021). DAS is also commonly used in oil and gas hydrofracking applications to detect fracture hits and clusters of microseismicity associated with the injection process, (Pichter, 2019).

A DSS integrator can also be used in conjunction with a DAS unit for Rockmass Response Monitoring. DSS utilizes the OTDR principle, like DAS, but specifically measures Brillouin light shifts to determine strain along an optical fiber, Figure 8. This method is sensitive to both strain and temperature; hence, accurate strain assessments often require complementary data from a high-resolution DTS depending on temperature variations along fiber.

While DSS excels in measuring static, absolute strain, offering immediate strain profiles upon installation, its dynamic strain tracking caps at around 10Hz. For faster strain changes, DAS is preferred, capable of higher sampling rates up to 100kHz and finer resolution, though it only measures strain changes, not absolute values, (Furlong, et.al 2023). Some DSS units in the market, with advanced interferometer, accurately assess Brillouin shifts, achieving high strain resolutions and a 60cm spatial resolution, with 10cm sampling. Capable of monitoring multiple cables, these DSS systems are versatile, functioning either independently or as part of a comprehensive suite including DAS/DTS, for a wide range of monitoring applications. In contrast, DAS and Carina systems specialize in dynamic strain measurements, achieving ultra-fine resolutions essential for detailed analysis over large distances.

To accurately measure strain, the fiber must be coupled to the object it is monitoring, e.g., for boreholes this typically means grouting. A DSS system can uniquely measure the absolute strain acting on tens of kilometers of fiber, and with a relatively low data volume. A superior DSS interrogator can have a resolution of ±1 με or

better with temperature correction, and with a spatial resolution of 60 cm.
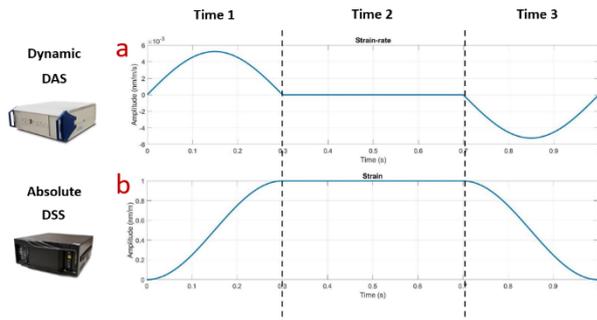

Figure 8   **Comparison of dynamic (a) vs absolute (b) strain by looking at the deformation of a cable at time 1, 2, and 3.**
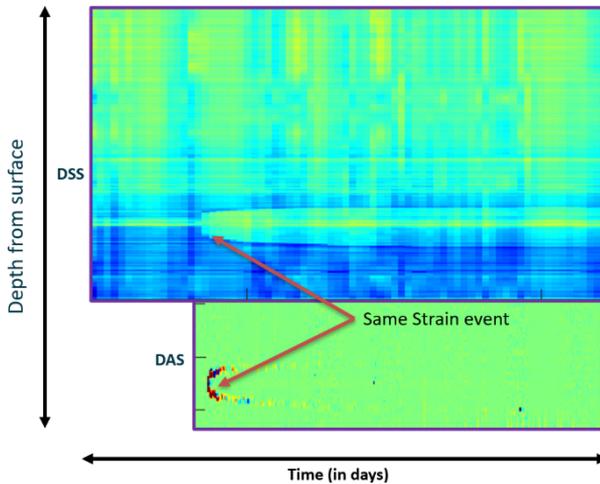

Figure 9   **a strain event recorded on a DSS unit (top) and DAS unit (bottom) at the same depth and time. The plots are rescaled and overlaid to show the beginning of the absolute strain on DSS and slow strain (strain rate) on DAS unit in one plot.**

The combined DAS/DSS strain measurements provide a higher level of accuracy in measuring the Rockmass response. Figure 9, from a DAS/DSS system installed at a block cave operation, shows how a DAS unit detects a *slow* strain (strain rate) event at a specific fiber location and time. At the same type, the DSS unit, measuring *absolute* strain on another fiber within the same cable, detects the same event at that time at a higher absolute strain. While the strain rate on DAS dissolves, the absolute strain remains persistent on DSS for days. The

combined data, therefore, indicates a fracture initiation event and the continued strain on the fiber. In this example, both DAS and DSS units continue to measure data on the entire length of cable, past the strain depth. This indicates that the strain event/fracture has not been significant enough to break the fiber cable. Once, the cave back progresses upwards and the fractures eventually break the cable by design, the DSS/DAS system continue to measure strain events on the remaining cable above the cave.

Another example from another cave operation is shown in Figure 10 where a DAS unit was used for detecting slow strain on a fiber cable installed in a deep hole to the side of the block cave zone. The continuous measurement of DAS system allows slow strain events to be plotted in real time and provide advanced notice ahead of cave/cable breakage to initiate safety protocols on site.
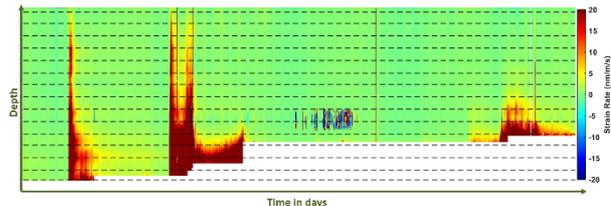

Figure 10   **Elevated strain rates on fiber cable ahead of fiber breakage and subsequent cave back progress upwards. Note that the end of the (broken) fibre is the transition from data to white.**
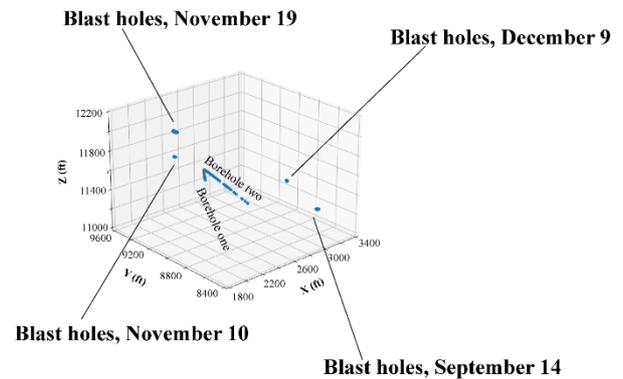

Figure 11   **layout of fiber instrumented boreholes and stope blast locations.**

1.2.4 Blast Monitoring using DAS

Recently the DAS system was used to assess the technology's capability for blast monitoring (Cheraghi, et al, 2024). Optical fiber cable was daisy chained in two boreholes underground each at 63 m and 143 m deep and a number of stope blasts were recorded and analyzed, Figure 11.

Figure 12 shows the raw DAS signals recording the blast signals at 200 millisecond and 25 millisecond apart. The raw signals also show the strength of each shot and indicating which shots were misfired.
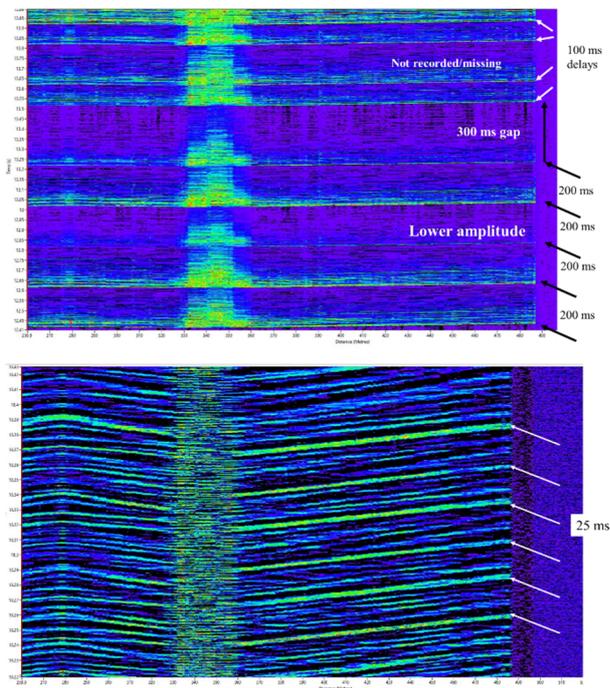

Figure 12 **unprocessed DAS data showing stope shots at 200ms apart (top) and 25 ms (bottom), (Cheraghi, 2023).**

The relative magnitude of the recorded data was analyzed for each stope blast to identify holes that misfired, or their functionality was not optimal/ as planned. Figure 13 shows relative energy of 176 shots in 3" holes, with delays from 200 ms down to 25 ms for the last shots of the stope blast. This initial trial demonstrates the use of DAS in monitoring stope blasting and optimizing stope blast design by detailed assessment of each shot's performance compared to design.
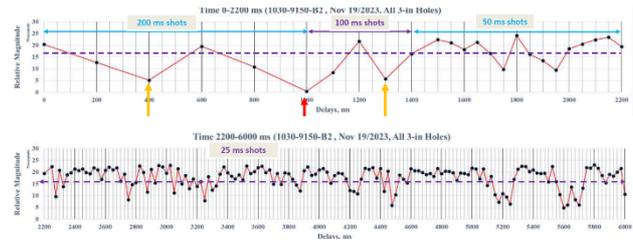

Figure 13 **relative magnitude of shots in stope blast, delays of 200, 100, 50 ms (top), delays of 25 ms (bottom), (Cheraghi, 2023)**

2 SYSTEM INSTALLATION

For open pit and underground applications, installing fiber optics cable in boreholes drilled through or adjacent to the monitoring volume is most common for deploying a DFOS system. The fiber cable is then grouted in boreholes and can be used for detection and monitoring of mining activities such as strain, seismicity, blast monitoring, and seismic imaging. It is often sufficient to use 2-4 boreholes and typically the existing exploration boreholes can be a desirable option to reduce drilling cost while enhancing the fiber array coverage. It is also common to install fiber cable in conjunction with other instruments such as beacons or extensometers in the same boreholes. There is often no interference between the optical fiber and other instrumentation and the fiber cable requires insignificant space in the borehole.

In microseismic/DAS applications to extend the size of a fiber array, multiple boreholes can be daisy chained using spliced fibers. This allows for the use of only one DAS interrogator, Figure 14 .For DSS applications, the use of an optical switch allows for monitoring of multiple individual fiber cables as close time intervals.

Overall, the footprint of a DFOS system is small. Fiber optics cables typically have a diameter of 5-10 millimeters, and weighs 30-100 kg/km depending on the application and cable design. Although the fiber optics core is delicate, the cables encapsulating the fiber are robust and built based on the condition of the environment they are deployed in to withstand the temperature, temperature, corrosion, or other site conditions. This allows relatively easy and cost-effective installation in deep boreholes

from surface, underground or along the mine tunnel. Figure 15 shows some examples of fiber deployment in surface and underground boreholes.

Due to the absence of moving parts and the ability to record for years with over-the-air updates, DAS systems require minimal maintenance and site visits, enhancing mine safety, reducing carbon footprint, and driving cost reductions.
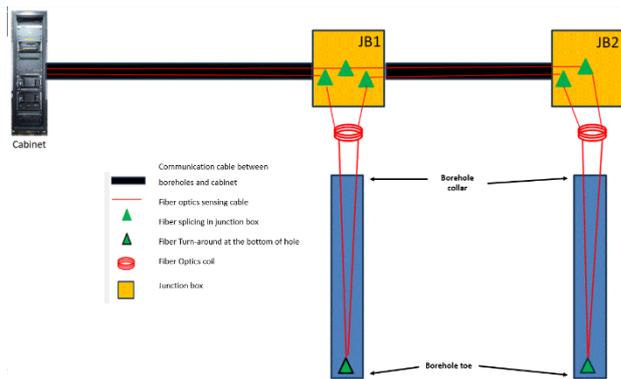

Figure 14   Schematic showing multiple boreholes daisy chained using spliced fibers.

Figure 15   Recent examples of fiber optics installation in surface and underground boreholes for monitoring.

3   DATA MANAGEMENT

Depending on the length of fiber cable and the acquisition settings, DFOS systems can generate a large volume of data. While this provides high resolution data on large monitoring volumes,

data settings and management should be planned based on monitoring objectives. In general, DTS and DSS systems generate smaller volume of data recording temperature and strain in nearfield. However, DAS generates large amount of full waveform far-field acoustics data that can becomes more complex with the numerous channels in a DAS array. Acquisition planning is necessary to select relevant channels with appropriate spacing and frequency for manageable data volumes. Additionally, the higher signal fidelity in terms of frequency, spatial density, and recording aperture can result in longer processing times compared to geophone recordings. Improving processing algorithms, increasing computing power, or decimating data are potential solutions to address this challenge and achieve desired processing periods. High quality, inexpensive solutions in data connectivity, processing power and storage (e.g., Starlink, cloud computing, RAID storage, etc.) are all but eliminated these previous impediments to technology.

4   CONCLUSION

This paper provided an overview of Distributed Fiber Optics Sensing technology and its early applications in assessing the Rockmass Response in underground mines.

Using combined DSS and DAS it is possible to measure the rockmass strain changes and microseismic response in real time.

The installation and grouting of fiber cable in boreholes is most common for cable protection as well as for recording high quality signals. A DFOS system can produce data typically every meter along the entire length of fiber and therefore data planning, especially for DAS/seismic applications is an important aspect of this platform.

The technology, although extensively used the primary solution in some other industries, is now advancing in the mining sector, and can be expected to become a standard monitoring platform in deep mines in the coming years, as the solutions matures. The early assessment of data shows potential for the technology to extract the rockmass stress and strain status

using the combined real time strain, and microseismicity. Further research is required to assess the capability of the technology for tracking gradual stress build up and stress release within the rockmass through distributed extension and compression analysis on fiber. As many such systems are installed at mines and with enhancing software and analytics platforms it can become possible to map the seismic hazard proactively at a high resolution and for large mining volumes.

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