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Acoustic device for recording and tracking rock hazards on the mining face

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Abstract

In the pursuit of enhancing personnel safety and operational efficiency in underground mining, this project introduces an innovative acoustic device for recording and tracking rock hazards on the mining face. This system combines advanced acoustic analysis with an ultra-wideband (UWB) location system to interpret sounds produced during rock mass sounding and scaling. The location system is georeferenced to the mine's local coordinate system using available survey pegs. By integrating these technologies, each acoustic data point includes a spatial XYZ coordinate which facilitates tracking of loose rock locations throughout the mining excavation process. This dual-sensory approach advances previous methods by leveraging the innovation of acoustic technology and tailoring algorithms to specific rock types, enhanced by the tracking function so that rock hazards encountered underground can be mapped and communicated to the operational team. The collected data offers a systematic approach to hazard identification and enhances mine designs and operational strategies by providing insights into the dynamic response of the rock mass during excavation under different mining conditions. This project offers a new approach to proactive hazard management, potentially transforming how mines are operated and mine designs monitored to ensure safety and efficiency.

Keywords: *acoustic analysis, UWB location, rock hazard detection, mining safety, algorithm development*

1 Introduction

Rock-related incidents in underground mining, particularly those associated with scaling activities, remain a significant safety concern in the South African mining industry. Scaling-related accidents often occur within stoping and development excavations around reef horizons being mined. Effective scaling starts with accurately identifying potentially hazardous loose rocks.

Currently the process of ensuring that work areas are safe involves tapping the roof of the mine with a pry bar (Van Wyngaardt 2010). 'Sounding' a rock involves evaluating the rock's structural stability by judging the noise generated when the rock is struck by the pry bar (Brink et al. 2016). The miner listens to the sound of the tap and, if the rock sounds loose, will attempt to pry it from the roof using the same pry bar for sounding the hanging wall (Van Wyngaardt 2010). Whether the rock is loose or not is determined by an experienced miner familiar with the sounding process. A rock mass considered sufficiently stable and safe will respond to the tapping with a relatively high-frequency sound, while a detached rock mass, regarded as unsafe, will respond with a relatively low-frequency sound (Brink et al. 2016).

Previous research by the Council for Scientific and Industrial Research (CSIR) led to the development of a device using thermal and acoustic technologies aimed at enhancing the making-safe process by confirming the presence of loose rocks using non-contact thermal methods and acoustic analysis.

However, this acoustic thermal device (ATD) did not fully address the need to track and monitor rock hazards across development cycles. Both the acoustic algorithm and the use of thermal signatures to identify loose

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rocks required refinement. Although the project provided some background on the thermal method used for rock hazard identification, it was identified that the potential and reliability of the acoustic method were more practical. Furthermore, by incorporating location tracking in addition to improving the acoustic algorithm, the next version of the system could provide a comprehensive solution for rock hazard management on the face through identification and monitoring.

2 Methodology for testing and development of the acoustic algorithm

The refinement of the acoustic algorithm began by considering the latest version of the ATD developed by the CSIR. The technology validation, conducted as the basis of this project, aimed to understand the tool's capabilities by addressing critical questions regarding its abilities and limitations within different mining environments. The initial underground technology validation process utilised the ATD in its then current format and construction, applying the already developed algorithms for assessing rock mass condition. For this initial part of the project no hardware development or software upgrades were made, so that the status of the ATD could be understood and used to guide further development. The ATD was considered an experimental development model or prototype tool at that time. Further development areas were identified through this project, and these were ranked by potential and identifying factors that influence the acoustic technology in this application. Two of these ATDs were manufactured for this phase of the project, and their individual results were differentiated as ATD 1 and ATD 2.

2.1 Equipment and set-up

2.1.1 Acoustic thermal device

Components: acoustic sensors, thermal camera, display unit, power supply

In Figure 1 an image of the ATD is shown with the current housing used to host the acoustic and thermal technologies.

Figure 1 The version of the acoustic thermal device used during thermal and acoustic validation trials

2.2 Validation methodology

The objective of the data collection was to encompass environments representative of where the ATD would be most beneficial, specifically focusing on sites where scaling practices were required, along with the environmental and lithological conditions typically encountered in platinum and gold mining environments in South Africa. The approach involved investigating potential differences between the platinum and gold environments based on on-reef and off-reef excavations.

The ATD was assessed by testing the acoustic and thermal technologies using distinct validation methodologies. The acoustic algorithm was tested in different geotechnical and operational environments. During trials, the ATD's results were compared against each other to obtain a consensus value. For this reason, both ATDs were used simultaneously at the same test site, ensuring comparable input data.

The thermal camera was exposed to different geothermal environments where the operator would use the thermal image to identify areas of interest. This paper will not report on the trial findings or the development being conducted on the thermal approach for identifying rock hazards on the mining face. A summary of the testing methodologies used is offered in Figure 2.

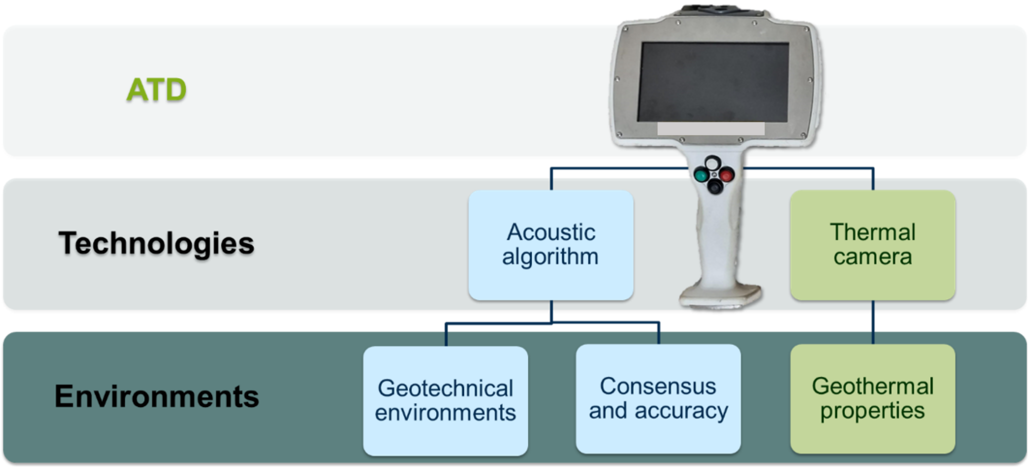


Figure 2 Testing methodologies specific to the two technologies used in the acoustic thermal device

2.3 Testing and validation procedure

When an underground crew member first observes a new area of rock that needs to be made safe, the thermal camera is pointed at the area of interest. If there are areas with a lower temperature resembling the outlines of a block of ground, they are considered potentially hazardous. Following this step or visual inspection an underground crew member sounds the rock with a pinch bar. The ATD detects the sound and the recorded waveform is displayed on the screen. It is then analysed based on its resemblance to the reference data entered into the ATD during algorithm training. A red screen indicates an unsafe or loose rock, while a green screen indicates a solid or safe rock surface. A valid captured sound should match an expected waveform and will then be registered in the ATD's algorithm as either safe or unsafe. Deviation from this standard waveform could indicate environmental noise, such as equipment operating in the area, or the sound of unknown lithology, e.g. a rock type that generates a different waveform. The three possible results for the ATD processing are shown in Figure 3.

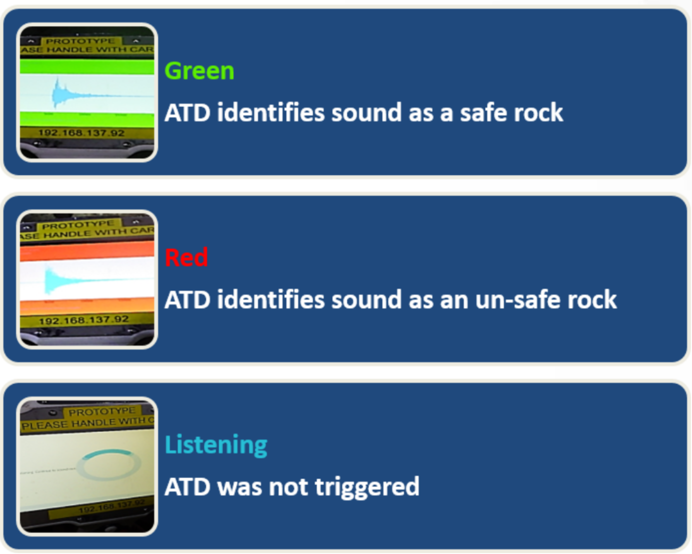


Figure 3 Acoustic thermal device read-outs delivered three results

3 Methodology for integrating and ultra-wideband location system with an acoustic thermal device to locate and track loose rocks in underground mining

Ultra-wideband (UWB) technology operates by transmitting data using extremely short pulses of radio waves across a broad spectrum. It can achieve centimetre-level accuracy in positioning and ranging applications, making it very useful as a location system in GPS-deprived environments. The integration of UWB technology in a location system with ATD aims to improve the efficiency of identifying and then tracking loose rocks in underground mining operations. This methodology outlines the steps required to utilise this as an integrated underground system.

3.1 Equipment and set-up

3.1.1 Ultra-wideband system

Components: UWB transmitters (tags) and UWB receivers (anchors) as shown in Figure 4, Supermicro server shown in Figure 5, data processing and display unit (tablet computer)

Figure 4 Tag (A) and anchor (B) of the ultra-wideband location system

Figure 5 Supermicro server which communicates wirelessly with the tags and anchors of the ultra-wideband location system

3.1.2 Systems integration

To integrate UWB tag location with ATD data, each ATD can be paired with an UWB tag to relay its location data to the Supermicro server. Attaching the ATD and UWB tags together is done manually, offering flexibility in attachment. A Supermicro server processes data from the tag, which records the XYZ coordinates so that syncing timestamps with the ATD can be done for correlation. Two datasets are thus created: one from the UWB location system, which records locally georeferenced coordinates with a timestamp, and the other from the ATD, which records rock hazards exposed by sounding practices, also with a timestamp.

The two datasets are combined so that the results from the acoustic algorithm and UWB data use timestamps to reveal loose rock locations. The integration of acoustic and UWB location data can be digitised on a mine plan using local georeferencing and this, in turn, creates a plan view of loose rock locations.

3.2 Data analysis

By plotting instances of loose rocks detected by the ATD with their georeferenced locations on a mine plan, a detailed map is created for trend analysis. This analysis may reveal, for example, that loose rock conditions commonly occur around geological structures or that certain intersection angles create more adverse conditions. It might also highlight inherent flaws in a mine design layout, where loose rocks are consistently found in specific layouts, configurations or mining sequences. Regularly integrating this data with existing mine design and planning software can inform decisions on support systems, excavation methods and safety protocols.

4 Data

4.1 Mining environments for acoustic data collection

4.1.1 Platinum mining environments

A total of 586 data points were collected across 52 sample sites. The number of sites visited in the platinum mining environment at shallow depth (<300 m below surface) and intermediate depth (>300 m deep) for each rock type is shown in Figure 6.

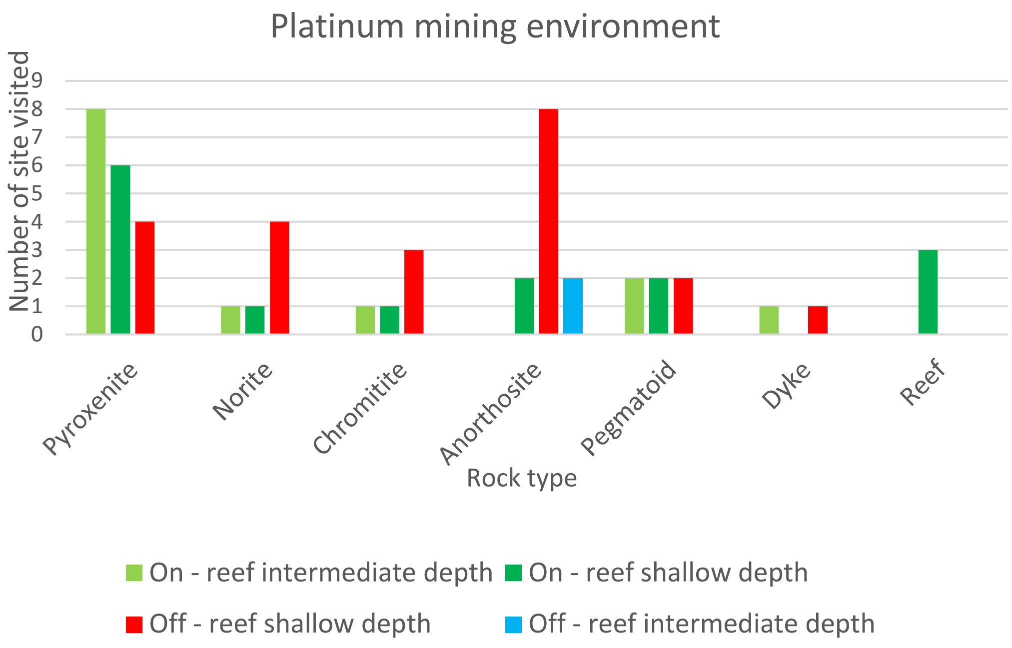


Figure 6 Chart showing sites of platinum rock types on-reef and off-reef at shallow and intermediate depths

4.1.2 Gold mining environments

A total of 376 data points were collected across 39 sample sites. The number of sites visited in the gold mining environment for each rock type is shown in Figure 7. The gold mines visited can all be considered deep to ultra deep, at depths exceeding 1,500 m below surface.

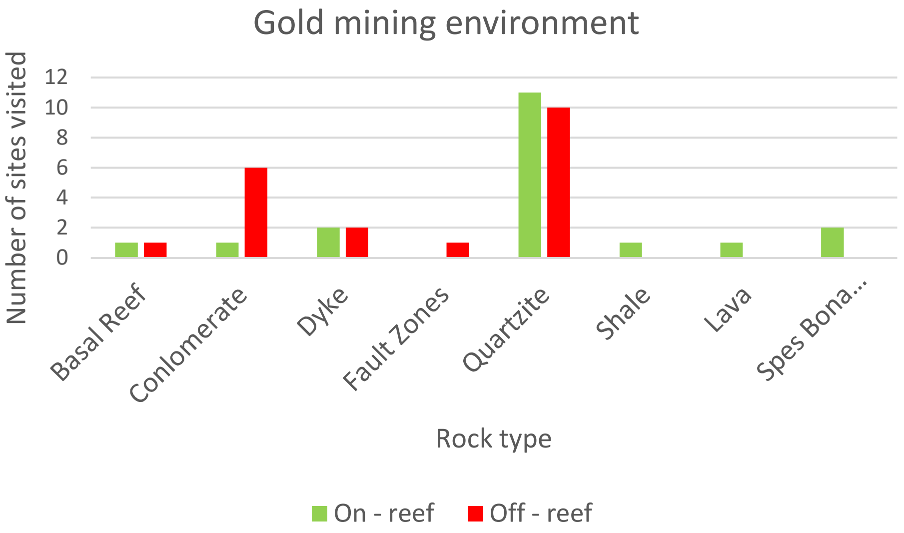


Figure 7 Chart showing sites of gold rock types on-reef and off-reef

4.2 Assessment criteria for acoustic data

Tables 1 and 2show examples of the gold and platinum environment parameters recorded during ATD underground tests. The data points collected were then analysed and used to assist with conclusions for this study.

Table 1 List of parameters recorded during platinum environment trials

Date and test site #	Pinch bar length (m) and material	Temperature wet bulb/dry bulb	Thermal identified	Type of excavation	Sounding location and ambient noise	Rock type	ATD acoustic results	Miner opinion and consensus between ATDs
Date of test and 1–15	0.9, 1.2, 1.8, 3.0 and aluminium/ steel	Measured by the miner	Yes/no	Haulage Crosscut Centre gully Gully Raise Travelling way	Hanging wall Sidewall Noise/quiet	Pyroxenite Norite Anorthosite Pegmatoid Reef Dyke Chromitite	Agree with the miner	Safe/unsafe Consensus

Table 2 List of parameters recorded during gold environment trials

Date and test site #	Pinch bar length (m) and material	Temperature wet bulb/dry bulb	Thermal identified	Type of excavation	Sounding location and ambient noise	Rock type	ATD acoustic results	Miner opinion and consensus between ATDs
Date of test and 1–9	0.9, 1.2, 1.5, 1.8, 2.0, 2.4, 3.0 and aluminium /steel	Measured by the miner	Yes/no	Development Gully Haulage Refuge bay Panel Crosscut	Hanging wall Sidewall Noise/quiet	Basal reef Conglomerate Dyke Fault zone Quartzite	Agree with the miner	Safe/unsafe and consensus

4.2.1 Date and test site

The date of the validation trial and the number of test sites where sounding was conducted in each shift were recorded. On average, four sounding samples were taken at each test site. This means that if there were 10 test sites at a specific mine there were typically around 40 sound samples taken at that site.

4.2.2 Pinch bar length and material

A pinch bar is the main tool used for sounding and scaling practices in South African mines. It is likened to a pry bar and requires a person to manually use it to sound and scale in an excavation. Pinch bars ranging from 0.9 to 1.8 m long were constructed as solid steel bars, with only the 3.0 m long pinch bar consisting of an aluminium tube with steel inserts. The condition of the pinch bar was not recorded but recognition is given to the fact that this could influence the sound created when striking rock and this will be recorded in subsequent algorithm improvements.

4.2.3 Temperature

The miner measured the temperature, both wet bulb and dry bulb, using standard equipment used in the mine.

4.2.4 Excavation type and sounding location

Validation trails considered various excavation types and the location within the excavation. The trial examined different excavations to account for acoustic variations related to the size and shape of the excavations, each featuring different lengths of pinch bars and distinct background noises. The collected data revealed that these factors collectively influenced outcomes where a change in pinch bar length correlated with alterations in both excavation type and its corresponding ambient sound.

4.2.5 Ambient noise

Background noise was assessed in a rudimentary manner, either being quiet in the excavation or noisy, based on the opinion of the trial participants. In excavations where the ambient noise was relatively low compared to the sounding waveform of the rock mass, the ATD would record a sharp increase in sound which then flattened out back to the low level of background noise. Figure 8 shows what a recognisable waveform looked like for the ATD. The waveform exhibits a rapid and sharp rise to a high amplitude, indicating a strong initial signal or impulse.

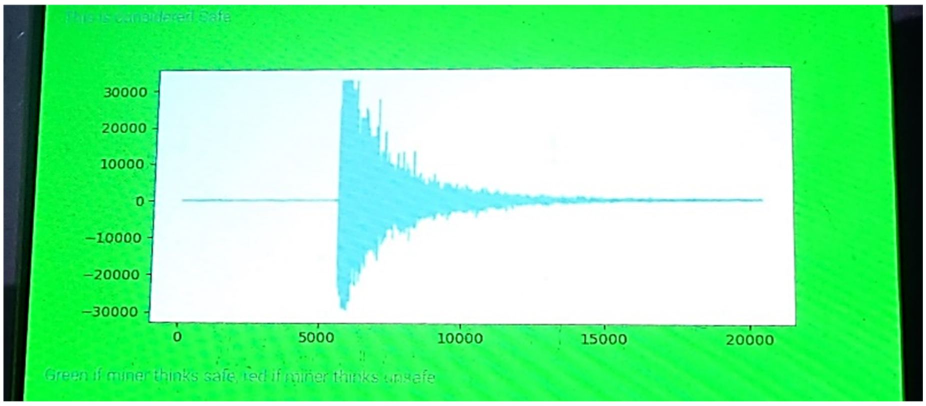


Figure 8 **An acoustic thermal device display of waveform illustrating a transient event with a significant and brief release of energy**

In excavations with high ambient noise which could overwhelm the rock mass sounding, the ATD screen recorded and displayed the ambient noise waveform. In such scenarios the ATD displayed a red screen, indicating that the rock mass was unsafe or, alternatively, the ATD algorithm had failed to recognise the waveform and so defaulted to indicating it was unsafe. Figure 9 shows an instance where ambient noise from mining operations flooded the waveform and the rock mass sounding could not be analysed.

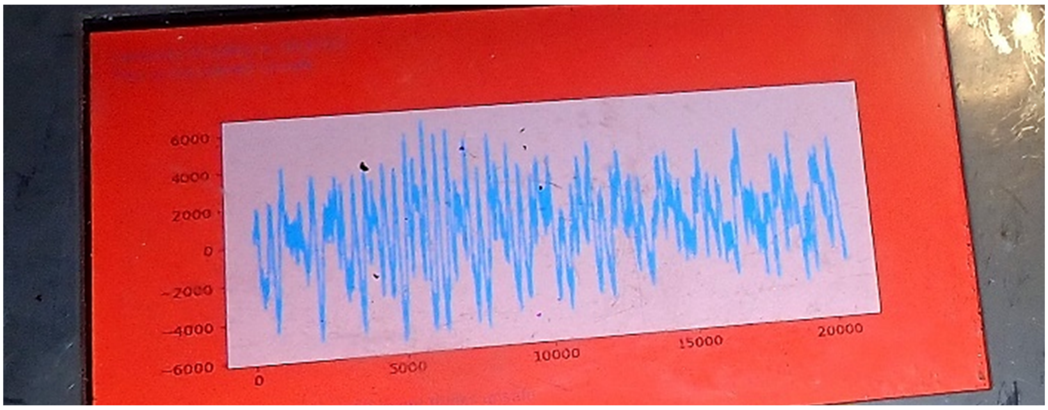


Figure 9 The acoustic thermal device recorded and displayed ambient noise as the recorded waveform

4.2.6 Rock type

The trial originally started with a list of typical rock types that would be investigated but additional rock types were added during the trial as they were encountered underground. The full list of rock types used during validation is shown in Table 3.

Table 3 Full list of rock types used observed during acoustic validation

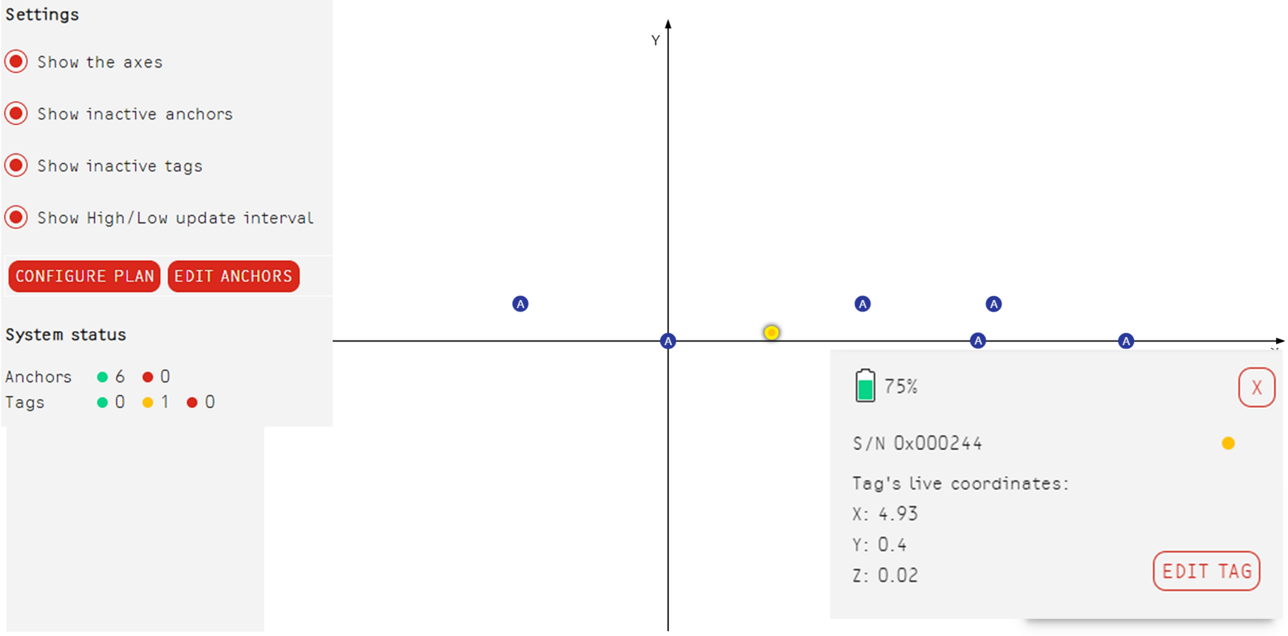
Platinum mining environment	Gold mining environment
Pyroxenite	Basal reef
Norite	Conglomerate
Anorthosite	Dyke
Pegmatoid	Fault zone
Reef	Quartzite
Dyke	Shale
Chromitite	Lava
	Spes Bona

4.2.7 Acoustic results and consensus

There were three results, as shown in Figure 3, that could be generated by each ATD which would then be validated against the opinion of the miner conducting the sounding and scaling. Agreement between the ATDs was used to derive a measure of consensus.

4.3 Location data collection set-up

A UWB location system can be deployed in an underground excavation where a crew is actively working and geospatial positioning would be of interest. This system is integrated with the mine's coordinate system by referencing its position to at least two survey pegs within the excavation. The coordinates generated by the UWB system assign an XYZ spatial position to the UWB tag (Figure 4 [A]). This tag can be affixed to the ATD, enabling real-time tracking of its location as it accompanies crew members engaged in safety activities throughout the excavation. During operations the UWB tag continuously tracks its position, providing location data whenever a loose rock is detected. In Figure 10 the position of the UWB tag is indicated with a yellow dot as it is being tracked in relation to the UWB anchors, which are depicted by the blue dots. Figure 10 is a plan view of the XY plane represented in the UWB location system user interface. Table 4 lists an example of the XYZ spatial dataset which is created with a timestamp by the UWB location system.



Settings

◉ Show the axes

◉ Show inactive anchors

◉ Show inactive tags

◉ Show High/Low update interval

System status

Anchors	● 6	● 0	
Tags	● 0	● 1	● 0

75%

S/N 0x000244

Tag's live coordinates:

X: 4.93

Y: 0.4

Z: 0.02

Figure 10 View of the ultra-wideband location system user interface showing the position of the tag in relation to the anchors displayed on the XY plane

Table 4 Example of location data created by the ultra-wideband location system

Anchor name	Anchor coordinates			Timestamp
	X	Y	Z	
0X41A	−3.09	7.50	0.62	20240703154530
0X85	4.83	−0.48	2.39	20240703154531
0X413	11.23	5.92	2.48	20240703154532
0X1F5	17.12	−0.72	0.71	20240703154533
0X43F	25.44	−1.05	2.22	20240703154534
0X18F	26.05	6.00	1.76	20240703154535

5 Research findings

5.1 Acoustics results summary

5.1.1 Overall acoustic performance

Figure 11 shows overall acoustic performance expressed as a percentage value of the agreement between the miner and the acoustic algorithm. The algorithm was originally developed in the platinum mining environment and all its reference data on acoustic waveforms were recorded in the platinum lithology. The ATD showed better acoustic performance in platinum mining environments compared to gold mining environments. In platinum, the ATD managed a 48% correlation between its validation results and the miner's opinion, which is about 12% higher than its overall performance in gold. Impressively, the agreement between the two ATD devices in the platinum was 90%, demonstrating their consistency in delivering reliable results under real-world underground conditions. The overall acoustic result emphasised that the algorithm requires reference data from the environment in which it will be used.

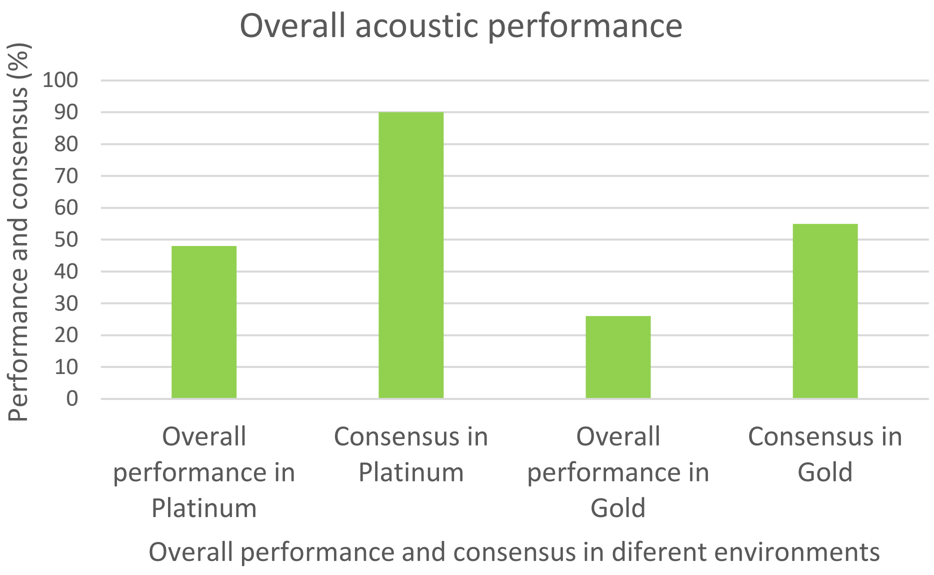


Figure 11 **Chart showing overall acoustic performance in platinum and gold mining environments, and how well the acoustic thermal devices agree with the miner and show consensus with each other**

5.1.2 Acoustic performance of the pinch bar and excavation properties

In every type of excavation, and even in each cycle of an excavation's development, changes to the type of pinch bar used are based on where safe making is required. These changing parameters influence the acoustics of the sounding and the acoustics offered by ambient sounds in the excavation. As such, the results from the excavation type, along with the type of pinch bar being used in that excavation and the ambient noise presented by the development cycle, all play a role in how well the ATD performs. The data collected for pinch bar and excavation types did not present a clear way forward for further development.

However, the ATD consistently performed better in all mining environments when background noise levels were low, as is shown in Figure 12. This makes sense as the equipment was not developed to isolate the sounding waveform from the ambient noise and, during algorithm development, areas with low background noise were used to generate reference waveforms.

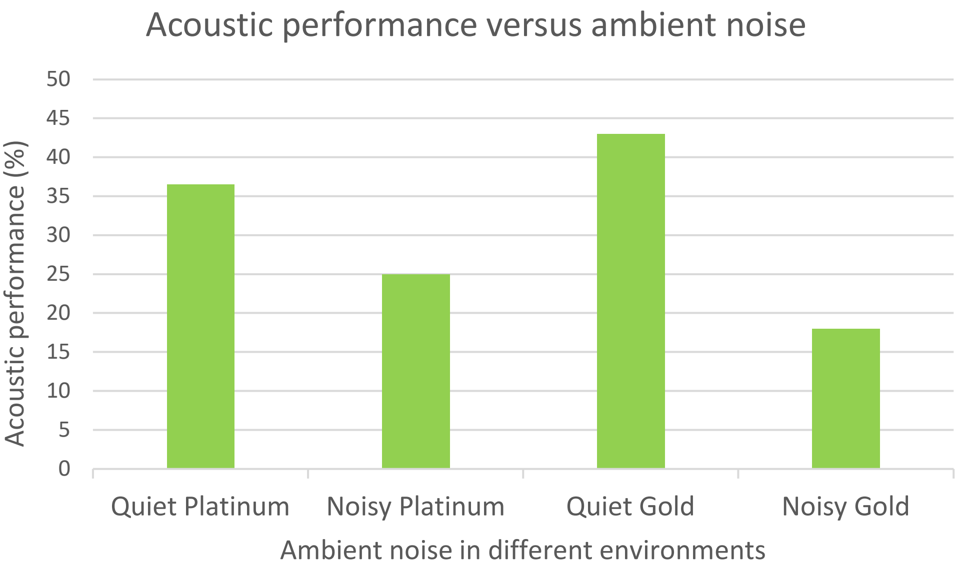


Figure 12 **Chart showing acoustic thermal device acoustic performance in relation to the ambient noise level**

Another important factor affecting the results was the location within the excavation where the sounding took place. In all mining environments, scaling on the sidewall (or face) demonstrated better ATD performance than that on the hanging wall, as shown in Figure 13. Generally, slabs forming on the sidewall can often be loose and separated from the rest of the rock mass without falling or toppling, as gravity is not the primary force causing instability. In contrast, loose rocks on the hanging wall are mainly influenced by gravity, and most large, thin slabs would fall during blasting. What remains are smaller rocks wedged as key blocks and similar rock fragments. Large, thin slabs produce a distinct low sound that is easily recognised by the ATD, whereas smaller rocks might produce sounds that are more difficult to detect.

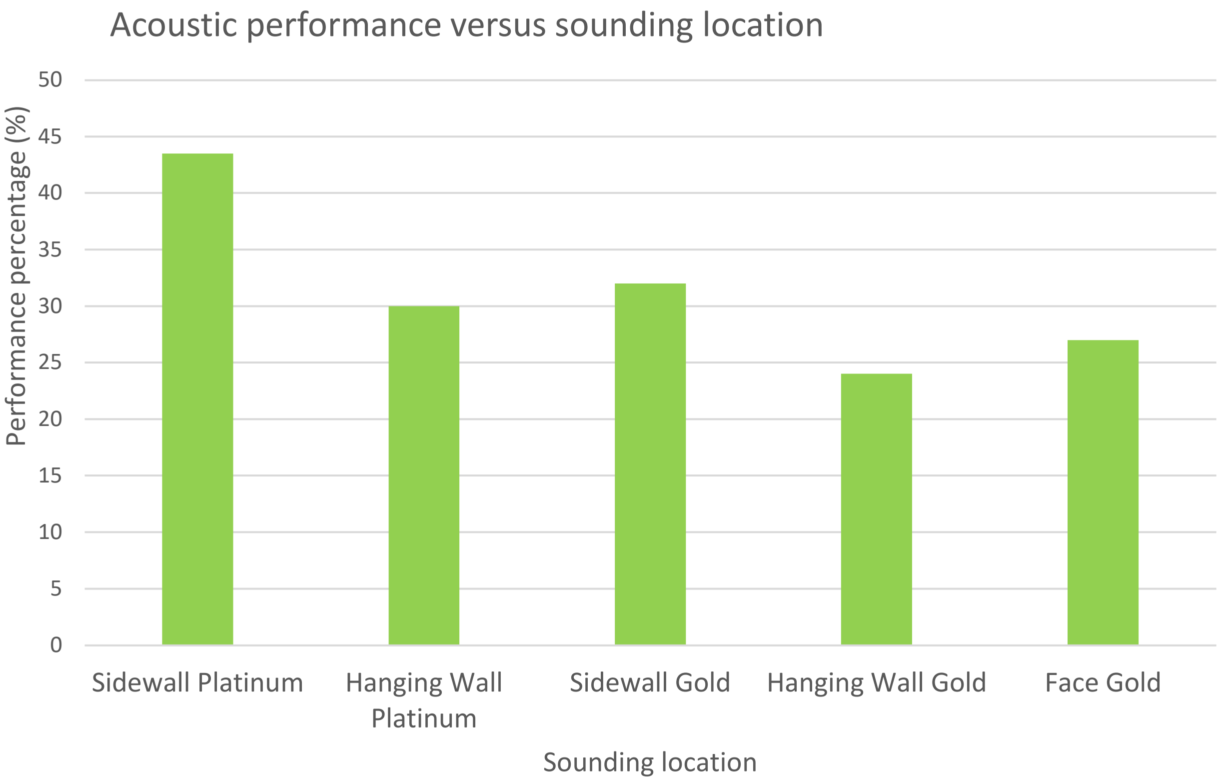


Figure 13 **Chart showing acoustic thermal device performance in relation to the location where sounding was performed**

5.1.3 Acoustic performance and rock type

This question was crucial as the trial aimed to determine if the ATD was more effective in identifying the condition of specific rock types. Given that the algorithm is currently heavily influenced by the lithology of platinum mines where it was last updated, the ATD performed reasonably well in the platinum trials. It showed better performance with rock types such as pyroxenite, pegmatoid, anorthosite and norite, and the performance values are shown in Figure 14. The difference in the sound generated by each rock type was apparent as the gold environment did not perform as well as the platinum environment. Rock types like the conglomerate formations and quartzite had low success rates, while the dyke showed promising results, as per Figure 15. Early indications from these trials suggest that some rock types produce a more recognisable sound, but it is assumed with sufficient data points in the algorithm, it can be calibrated to achieve improved results across more rock types.

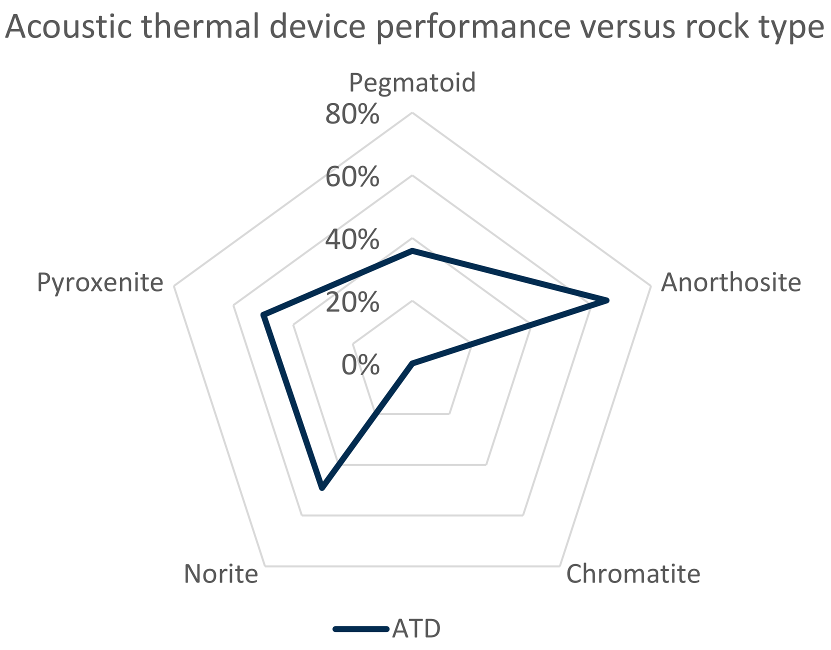


Figure 14 **Radargram of the two acoustic thermal devices' performance in relation to rock type testing in a platinum mining environment**

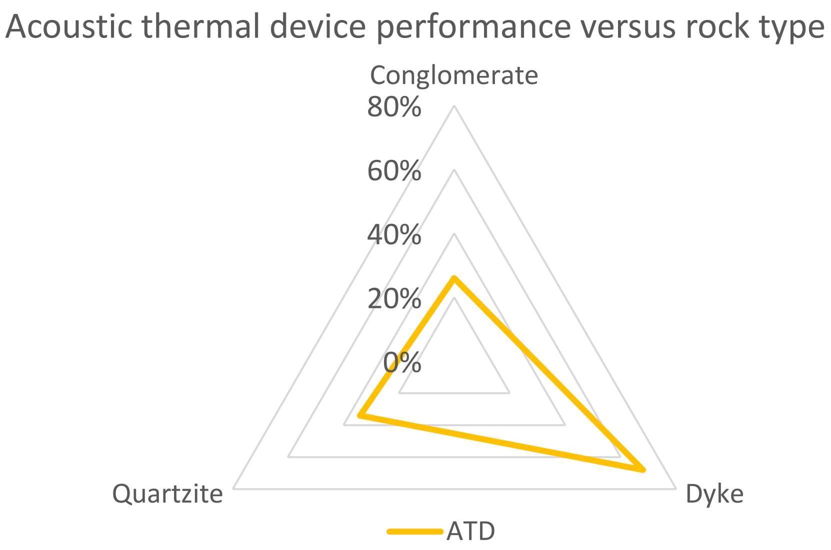


Figure 15 **Radargram of the acoustic thermal devices' performance in relation to rock type testing in a gold mining environment**

5.2 Data integration summary

Data integration begins by combining the two datasets produced by the ATD and UWB location system/s. Since both datasets were compiled using timestamps, these are used to align the ATD results with the XYZ coordinates produced at the corresponding time. Since the UWB location system is referenced to the mine's local coordinate system, each instance where loose rock was identified can have an XYZ coordinate that could be plotted on the mine's survey or planning software platform.

By plotting instances of loose rocks detected by the ATD with their locations on a mine plan, a detailed map could thus be created for trend analysis. It is expected that the map will highlight that loose rock conditions commonly occurred around geological structures or at certain intersection angles, revealing potential for improvements in the mine design layout. Regularly integrating this data with existing mine design and planning software can inform decisions on support systems, excavation methods and safety protocols. To better explain the concept, Figure 16 presents a concept drawing showing consecutive face positions of a narrow tabular stope. A cross symbol is used to indicate positions of loose rock that were encountered during sounding and scaling across four consecutive face advances. For demonstration purposes, Figure 16 shows that there is an accumulation of loose rock encounters in a certain part of the panel. This would alert the operational team to investigate the situation and assess possible resolutions.

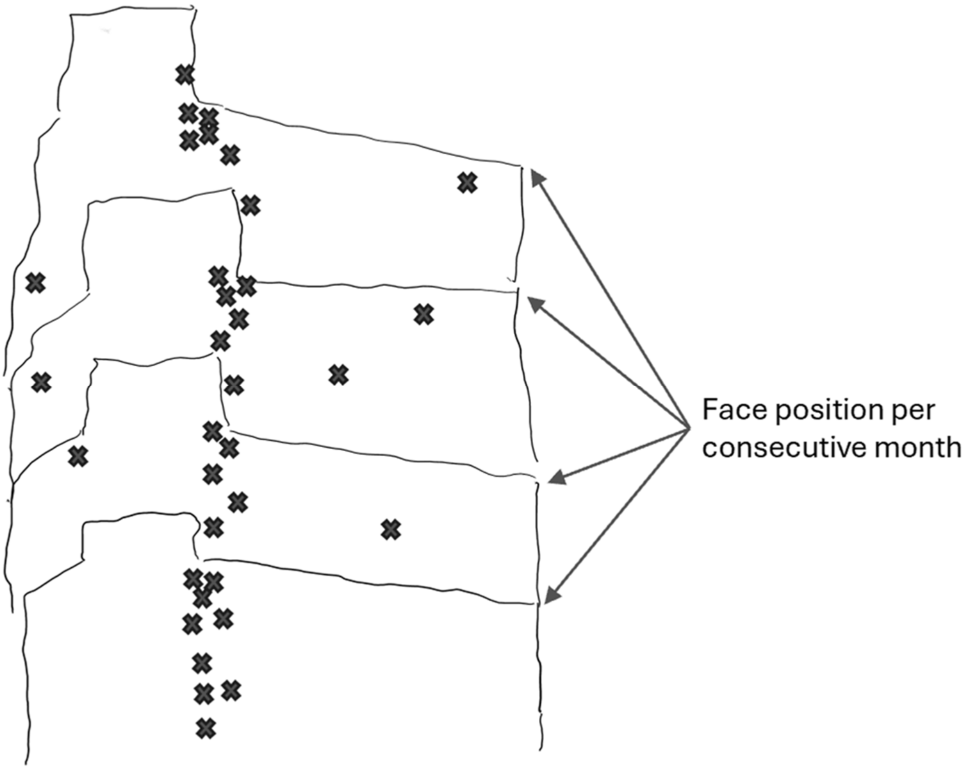


Figure 16 A concept drawing showing consecutive face advances of a panel face with loose rock hazards identified and plotted to enable observation of potential trends in a dataset

6 Conclusion

The performance of the ATD varied across different rock types and excavation environments, exhibiting better results in low-noise conditions and with specific lithologies. The primary focus of the project was on guiding software development for the acoustic algorithm, specifically to understand the necessary refinements to enhance its performance and reliability in identifying loose rock hazards. For optimal performance the specific rock type needs to be pre-registered in the device's algorithm so that sufficient reference data is available for identifying and processing events. The next step will focus on software development for the acoustic device, with an emphasis on algorithm refinement through quality data.

On its own the ATD lacks the functionality to track loose rock and monitor changes in rock mass across mining cycles. Additionally, it is unable to correlate acoustic data with spatial information within the mine, which limits its utility for ongoing monitoring and trend analysis. Moving forward, the ATD results merged with location information can inform mine design changes and enhance hazard communication across shifts.

This paper underscores the importance of, and potential for, combining acoustic and UWB location data to develop a more nuanced understanding of rock hazards in mining operations, thereby facilitating targeted interventions and improved safety measures.

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