Characterising the Internal Composition of Rock Piles Using Ground Penetrating Radar

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I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma at Charles Sturt University or any other educational institution, except where due acknowledgment is made in the thesis. Any contribution made to the research by colleagues with whom I have worked at Charles Sturt University or elsewhere during my candidature is fully acknowledged.

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Allen Max Benter
October 2014
Glossary

$\epsilon$ Electric Permittivity.

$\mu$ Magnetic Permeability.

$\sigma$ Electric Conductivity.

**CFDS** Centroid Frequency Down Shift.

**CRIM** Complex Refractive Index Model.

**DFT** Discrete Fourier Transform.

**GPR** Ground Penetrating Radar.

**GPS** Global Positioning System.

**LHD** Load Haul Dump.

**LLL** Landau and Lifshitz, Looyenga model.

**MHS** Material Handling System.

**NDT** Non-Destructive Testing.

**PEC** Perfect Electric Conductor.

**VOF** Vertical Offset Filter.
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Abstract

Oversized fragments appearing at the drawpoint pose a major problem to all block cave mines. If an oversized fragment is not identified by the extraction vehicle operator, it has the potential to block the Materials Handling System (MHS), preventing subsequent loads from being processed and reducing overall efficiency in the mine.

Existing techniques for automated rock fragment detection at the drawpoint use optical cameras to identify individual fragments, but these methods are limited to detecting surface fragments only.

This thesis presents a method to identify oversized fragments below the surface of a rock pile using Ground Penetrating Radar (GPR). The radar response to the rock characteristics was determined from experimentation in the laboratory. Different antenna arrangements were tested and a method for auto-calibration of zero-time at a remote antenna developed.

Two approaches were taken in this thesis to identify oversized fragments below the surface of a rock pile.

Firstly, 2D imaging of the individual fragments within the rock pile was tested. A new method to improve the contrast of radar images of the internal structure of the rock pile using the physical motion of the antenna was developed.

Secondly, a volumetric measuring approach was developed. This method measures various radar signal properties from the rock pile volume rather than mapping individual rock pile constituents. One benefit of this approach is the speed of acquisition and determination, allowing the presence of an oversized fragment in a rock pile to be inferred from signal properties.
Results from laboratory experiments are presented which demonstrate volumetric analysis is capable of detecting oversized fragments in a rock pile, and that this method could be used to identify oversized fragments at a mine drawpoint. Identifying oversized fragments at the drawpoint will assist in the reduction in crusher blockages and reduce unnecessary vehicle movements, improving the efficiency of ore extraction and metal recovery.
Chapter 1

Introduction

Block caving is an increasingly popular method of underground mining as it has one of the lowest cost per tonne of any mining method. After fracturing, the ore within the caved area (see Figure 1) falls under gravity and flows to drawpoints where the ore is ‘drawn’ from the ore body, crushed to a uniform size, and transported to the surface for processing.

A major problem in the extraction process is the appearance of oversized fragments at the drawpoint. This thesis presents a method of identifying large fragments hidden beneath the surface in a rock pile. The results of laboratory experiments are discussed which show that rock piles containing large, buried fragments can be identified.

In this chapter, the background to the problem is presented by briefly explaining the mining process and identify the problem of oversized fragments. This is covered in Section 1.1. Oversized fragments, and the way they are currently identified at the drawpoint, is explained in Section 1.2 followed by a brief discussion on the economic impact of Material Handling System (MHS) blockages (Section 1.3).

1.1 Mining Background

The mine investigated in this project was Ridgeway Deeps, part of the Cadia Valley Operations of Newcrest Mining Ltd.

As the fractured ore body falls under gravity, the rock continues to fragment. The material is extracted at the drawpoint by Load Haul Dump (LHD) vehicles (see Figure 2) and transported to the primary crusher where the fragments are reduced to a uniform size.
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Figure 1: The ore body caves after fracturing and the fragmented material flows through the drawbells to the drawpoints for extraction.

After primary crushing the ore is transported to the surface, in this case by conveyor, where it undergoes further milling before flotation extraction of gold, copper and other metals.

The initial construction of a block cave mine tends to take some years with a high investment of capital required before production commences. Once extraction of the ore is under way, the operating costs tend to be the least expensive of all underground mining methods.

Block caving is capable of a high rate of extraction and provides an efficient operation in removing the fractured ore. If there are delays or inefficiencies in the production cycle these can reduce the throughput and affect profitability of the mine. There are two types of problem that can influence production levels from the drawpoint: hang ups and oversized fragments [4].

Hang ups block the drawbell preventing any further rock flow and may be low or high in relation to the drawpoint. They also may involve either one large fragment, or a collection of locked fragments. This type of problem has impacts on ore extraction rates and sequencing. They can be dealt with either by water blasting or concussive blasting, however if this does not dislodge or break the hangup, the larger fragment(s) can be drilled, charged with explosives and blasted to further reduce the size and allow ore flow to resume [5].
Oversized fragments are those that present at the drawpoint, but are too large to be efficiently handled by the LHD and/or the crusher. In the case of Ridgeway Deeps mine, the LHD has a bucket volume of about $7.5\, m^3$ and can haul fragments up to approximately $6\, m^3$. Due to the crusher installation at Ridgeway Deeps, any fragments larger than $1\, m^3$ will not fit through the crusher feed bin and are considered oversized. These large fragments become potential blockages in the MHS, and may affect production output.

This thesis only deals with the second problem, that of identifying oversized fragments.

Figure 3 shows a number of large fragments, including one over 1 metre in width. Each of these fragments has the potential to block the crusher. As these fragments are visible at the surface, they are easily dealt with through secondary breaking strategies. When a number of drawpoints are closed because of hangups or oversized fragments, the extraction drive is closed to allow a secondary breakage crew to enter. The breakage crew will proceed to clear hangups and oversized fragments before allowing the LHDs to re-enter the extraction drive to continue ore extraction. Oversized fragments are blasted at the drawpoint to a size which will fit through the crusher.

The problem of oversized identification is apparent when large rocks are obscured from the view of the driver, or remote operator. Figure 4 shows a drawpoint with smaller...
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Figure 3: An oversized fragment presents at the drawpoint. Fragments such as the large pieces visible are potential blockages at the crusher and reduce overall mine efficiency. The coloured ball is used for scaling purposes in manual image analysis.

Figure 4: A typical drawpoint from which fractured ore is to be 'bogged'. Oversized fragments are not visible, but may be present beneath the surface.
1.2. IDENTIFYING OVERSIZED FRAGMENTS

Oversized fragments can interrupt operations in a number of ways. When an oversized fragment is present, the drawpoint must be closed which impacts on the sequencing of extraction and maintaining desired flows through the ore body.

The low extraction costs of block caving relies on efficient and fast LHD movements. These movements are planned to provide the shortest driving cycle. When oversized fragments appear they reduce the efficiency of LHD movements by requiring the vehicles to exit a drawpoint unladen before continuing to the next extraction point in the sequence.

Current operations have a driver on-board the LHD who is able to observe the drawpoint for oversized fragments. Oversized fragments may be hidden or partially obscured from the cockpit view of the driver. Mine operations are gradually being transformed with semi-autonomous vehicles [6]. New LHDs are remotely driven from the surface using vehicle mounted cameras (see Figure 6). Poor imaging and display conditions, as shown in Figure 5, present additional problems for remote operators in identifying oversized fragments.
Fragments that are too large to fit into, or be lifted by the LHD, will be detected by the driver when an attempt is made to gather a load. In this instance, the driver can abort collection and inform the scheduler that the drawpoint is now closed. If the driver sees a fragment too large for the crusher after collecting the load, the driver must dump the load and the drawpoint is closed until such time that a secondary breakage crew can enter and break the rock. Aborting the collection after entry to the drawpoint will affect efficiency by increasing the time between successful loads.

The worst case is when oversized fragments that are too big for the crusher are not visible until they are dumped into the crusher. Should this happen, they are likely to become an MHS blockage and prevent subsequent loads from being processed. In this case, the large rock must be broken by remote rock hammer rather than blasting, which prohibits further loads from being processed and may take excessive time.

In some mines the use of a steel grate which filters the rocks (known as a ‘grizzly’) is used to block large fragments from entering the crusher or ore pass system. The mine under study uses a grizzly and it has a tendency to cause extra blockages by rocks locking together and requiring ‘encouragement’ by the rock hammer to break and fall through. The ideal solution is to avoid blockages all together and leave the problem – the oversized fragment – at the drawpoint for processing.

### 1.3 The Economic Impact of Crusher Blockages

The mine operator estimated that:
1.4. RESEARCH PROPOSAL

1. the minimum time for a return trip from a drawpoint to the grizzley would be approximately 30 seconds;

2. on average there would be one oversized fragment per thirty loads;

3. it would take about 3 minutes to clear the blockage at the grizzley;

4. multiple LHD vehicles operate simultaneously on different extraction shafts with unique entry points to the same crusher unit.

In the three minutes the grizzley is out of action, there could be up to 9 loads that would not be processed.

In 2012 total mine production at Cadia Valley was 16,000,000 tonnes of ore and 473,200 ounces of gold [7]. With the existing LHDs capable of 15 tonnes, this represents in excess of 2900 loads per day, each load containing $\frac{1}{2}$ troy ounce of gold and about 40 kg copper. Based on the estimates above, nearly 100 loads per day would contain oversized fragments. The worst case scenario (all blockages occurring) could result in 900 loads being lost from a days production.

By detecting the rocks at the drawpoint before the LHD has lifted them, and thus preventing them from being dropped into the crusher, the mine can avoid this impact on overall mine efficiency. The problem of dealing with the oversized fragments would then be shifted from the critical crusher location to the non-critical drawpoint. Secondary breakage can then occur at a scheduled time with minimal impact on production.

1.4. Research Proposal

Reducing the impact of oversized fragments will improve overall mine efficiency and drive down operating costs. This will maximise mine operating profits when commodity prices are high, but also assist with keeping the mine profitable should commodity prices fall.

Existing identification methods, including automated computer vision systems, rely on the oversized fragments being visible on the surface of the rock pile. Poor lighting, dust and low contrast display units can contribute to a driver or remote operator not identifying a large rock at the drawpoint. Driver behaviour around production quotas may also contribute to large rocks being collected so that wasted time is not attributed to the driver.
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The major failing of the existing visual system though is its inability to penetrate the surface of the rock pile and be able to identify large rocks that are buried. An automated large rock detection system would therefore be required to detect when a large rock is buried within the rock pile at the drawpoint.

Accordingly, the central question addressed in this thesis is:

**Can oversized fragments buried in rock piles be detected?**

Mine operations constraints are also an essential part of a viable solution to the above research problem. This thesis considers two additional critical constraints in addressing the central question.

1. **Can a determination be made as to the presence of a large fragment given the time constraints of the mine?**

   The mining operations require efficient bulk handling of the ore which minimise vehicle movements. Once an LHD has obtained a load of ore, it is expected that the load will be processed by the crusher. If a large rock is detected in the bucket of the LHD, the time to collect, identify and dump the load is considered lost time and will contribute to mine inefficiencies. Hence, the determination must be made within the time constraint of the vehicle returning to the drawpoint for the next load.

2. **Can a detection system be designed such that it would be suitable for installation within an underground mine?**

   Further, the system installation and maintenance must consider the operational and engineering requirements of the underground mine. The mining environment provided a number of additional practical constraints which were considered during development. All equipment used underground must be robust to withstand normal machinery use and maintenance. Also, the analysis of data cannot be computationally expensive to allow for on-board processing to reduce decision times.

   The detection method that has been chosen is Ground Penetrating Radar (GPR) as it offers the ability to penetrate the rock pile. GPR has been a proven technology employed in the mining, geotechnical and geological industries for detecting objects underground.

   In order to use GPR for imaging the rock pile, and to answer the central research question above, a number of other questions needed to be answered:
3. **Is there a difference in the electromagnetic signal between fragmented rock and solid rock?**

4. **Is there a relationship between the ore sample’s constitutive characteristics and the bulk density of the ore?**

### 1.5 Thesis Outline

Chapter 2 of this thesis examines the use of computer imaging in the mining industry, including Ground Penetrating Radar (GPR), to image subsurface features. The constitutive relationships affecting electromagnetic signal transmission are introduced, together with a review of mixture models for measuring the effect of heterogeneous materials on these constitutive relationships.

Chapter 3 characterises the GPR system employed in this research. GPR images are constructed from multiple scans resulting in a 2D data compilation. Standard processing techniques used to prepare the data for compilation into images are discussed. A new technique called the Vertical Offset Filter is presented which can provide mechanical control of image contrast.

A volumetric analysis technique that would enable identification of buried oversized fragments is investigated in Chapter 4. Radar measurements are presented in this Chapter showing how different fragment sizes and sample bulk densities behaved under radar illumination.

Chapter 5 presents the results of radar measurements and statistical analysis upon a large, complex sample set and shows that oversized fragments can be detected. Chapter 6 concludes with a discussion on future directions of the research.

### 1.6 Original Contributions

The key contribution of this thesis is a solution to the central question posed in Section 1.4:

- the development of a method to detect large rocks that are obscured from view within a rock pile. The method is capable of distinguishing between large and small fragments and air pockets in a medium scale model of a drawpoint, and is robust to
collections of medium sized fragments that aggregate and appear as a solid piece. The solution identified is also fast and computationally inexpensive as required by the mine operators.

As a result of this research work other contributions to the knowledge of ground penetrating radar signal analysis include:

- A new algorithm to reduce clutter in GPR images was developed and described in Chapter 3. While the enhanced GPR images proved unsuitable for identifying oversized rock fragments during a mining operation, the clutter reduction algorithm promises to be beneficial to other GPR imaging applications.

- A major problem in GPR applications exists for spatially and temporally separated antennas where the signal time zero drifts. An alternative approach to mitigate the drift for trans-illumination surveys has been demonstrated in Chapter 4.

- Further, a method of identifying signal arrival time using the Hilbert Transform has been demonstrated in Chapter 4.

- The relationship between permittivity and bulk density of the material has been demonstrated in Chapter 4 to hold for fragmented, irregular shaped and sized material of assumed similar chemical composition.

- During the investigation it was also shown that there is a measurable difference in the electromagnetic signal after propagating through solid rock compared to fragmented rock. This difference is observable in at least three signal properties and is discussed in Chapter 5.

The research outcomes presented here have been accepted for publication at mining and geophysics conferences and in relevant peer-reviewed journals, as listed in Publications. The results have also been demonstrated to the mine operators and further research projects extending this research are to start in 2014.
Chapter 2

Literature Review

This chapter reviews computer imaging systems used in the mining industry, particularly where they are used for rock fragment imaging. Ground Penetrating Radar (GPR), and the basics of its operation, is introduced followed by a review of GPR image processing methods. The effectiveness of GPR as an imaging tool relies on the material through which the signal is penetrating. Material properties, and their effect on the GPR signal, are explored. Mixture models are presented and how they can represent heterogeneous materials.

2.1 Computer Imaging in Mining Environments

The mining industry has long employed various computer imaging techniques to enhance their understanding of the mining environment, and improve the operation and efficiency of mining facilities, both above ground and underground. Images of large scale, subsurface geological structures are commonly generated by seismic imaging. The increasing needs of security and safety are driving the adoption of optical imaging systems in mining operations around the world.

Finding a large rock in a rock pile with GPR has been described as trying to identify a large piece of glass in amongst a pile of glass shards [8]. The problem is not just identifying the fragment, but differentiating the fragment from the background which looks the same.

In underground operations, rock fragmentation imaging can be achieved at various stages in the mining production cycle. At all stages, problems such as dust and lighting affect the implementation of an effective and reliable imaging system [9]. This section reviews
a number of candidate imaging systems currently employed in the mining industry.

2.1.1 Optical Imaging Systems

Computer vision using optical camera systems has been employed in a variety of applications including surveillance [10], manufacturing [11], object recognition [12], and robot navigation[13]. Within the mining industry, optical computer vision applications have been used to identify mineralogy [14]; grade aggregate in place of conventional sieves [15]; detect rocks capable of blocking equipment [16] and determine the degree of fragmentation as a result of blasting to improve explosive efficiency and placement to generate more reliable fragmentation [17, 18, 19].

Prior to computer vision systems, fragment sizes and distributions as a result of blasting or crushing were determined by passing the crushed material manually through screens of different sizes. The authors in [20, 21] developed a computer vision system to analyse fragment shape of aggregate offering fast and objective measurement of each fragment.

One of the major problems experienced with computer software packages was overestimation of the size of fragments as a result of the apparent fusing of small particles being detected as larger fragments. Conversely, software also suffers from disintegration where large fragments are incorrectly detected as a number of smaller particles [22].

A number of commercial software packages exist to determine fragment size and distribution including [23] and [24]. A comparison of manual image analysis and software image analysis was undertaken in [22], where it was found that the results were not consistent between the two methods although, after merging a number of photographs together, one of the software packages produced results comparable to manual methods. It was also noted that while manual analysis was very time consuming, the software packages required additional manual pre-processing to improve the results which limit their effectiveness and objectivity.

The opportunities to capture images are limited to a few locations within the mining process. After blasting the material remains at the draw point until collection. This is the most difficult to capture due to the irregular surfaces of the pile that is presented to the capture device.

Once collected by an LHD vehicle, the ore material is confined within the bucket, and can be captured either by a vehicle mounted camera or at a common image collection point which the vehicles pass on their way to the crusher [21, 25].
The techniques described in [26] capture images of fragments within a feed chute to dual crusher units. Heavy steel chains manually filter the fragment streams into a single layer, enabling the computer vision system to identify any fragments capable of blocking the crusher. If such a fragment is present in one of the chutes leading to the two crushers, that crusher unit can be shut down to enable secondary breaking without interrupting the other crusher.

Image capture for fragmentation analysis is possible post-crusher, however these scenarios are outside the scope of this thesis. As pointed out in Chapter 1, this thesis is concerned with identifying the presence of large fragments pre-crusher.

One of the benefits of using an optical vision system is the similarity to current work processes. Current semi-autonomous vehicles send streaming video to a remote tele-operator who makes the determination regarding the size of the fragments prior to collection. This image is typically from a single camera system mounted centrally on the vehicle. An optical computer vision system for fragment detection may be able to utilise, or work alongside, the current imaging systems on such vehicles. This could provide an opportunity to augment the vision system for the remote operator.

**Intrinsic Problems**  The major problem with optical vision systems, is the image is only of the surface of the pile [27] and efforts to extract 3D information must make assumptions about depth in the third dimension [18]. Any large fragments that are partially or fully obscured by surface fragments will not be identified and may block the crusher if collected.

A probability model of a laboratory pile to determine the internal structure of the pile from optical surface images has been developed [28]. This method relies on multiple measurements of the surface of the rock pile, however at the drawpoint only one surface is seen before the LHD extracts the load, altering the composition of the pile. Further, the Author noted that any segregation or disturbance, such as vibration by a loader, could lead to catastrophic error.

An augmented vision system using a laser scan line has been described in [29]. This method, however, only observes surface rocks, excluding all buried and overlapped rocks and is currently working post crusher as it is not suitable on its own at the drawpoint.

**Extrinsic Problems**  Computer vision systems experience extrinsic problems particularly in challenging environments. An underground mining environment is a dark and
dusty environment. Using standard lighting, dust can prevent the capture of clear images that would enable the determination of surface fragment sizes. This can be reduced by the use of an infra-red imaging system, which would also remove the need for additional broad spectrum lighting systems [9].

Camera systems mounted on mining vehicles also suffer from the vibrations of motion and engine operation, although electric vehicles would reduce the effects of combustion vibration and particulate matter in the air. Applying image stabilisation filters to the captured image sequence could reduce the noise caused by vehicle vibrations.

One other disadvantage of using fixed or vehicle mounted optical cameras is a dependency on camera calibration for position and direction [30]. Unlike sonar or a laser range finder the distance information for single optical cameras is obtained from extrinsic factors, where the distance to the pile is pre-measured. If the camera’s position changes slightly, this could lead to incorrect distance information, and thus incorrect sizing, requiring physical re-calibration. To avoid measurement in dangerous locations such as at the drawpoint, a stereo camera set-up can be used whereby the distance is obtained from the correspondence between image views.

Regardless of the number of cameras in use, or their configuration, the major disadvantage of optical systems for hidden fragment detection is that the image obtained is of the surface only. For fragments that are mostly, or completely, below the surface, optical cameras will not be able to provide sufficient information to enable a determination. Therefore, for the current application, a penetrative imaging system is necessary.

### 2.1.2 Penetrating Imaging Systems

A number of penetrating imaging techniques are available, and have been actively used in the mining industry. Sound has long been used by the mining industry to investigate geophysical structures beneath the surface of the earth. Ground Penetrating Radar has been used in the construction industry and mining particularly for shallow depth imaging.

**Acoustic Imaging** Acoustic imaging includes sonar, seismic and ultrasound imaging techniques. Sonar is a navigation and ranging tool that is not suitable for the current application as it is not a penetrative imaging system.

Seismic imaging has long been used by the mining industry to obtain details of large
2.1. COMPUTER IMAGING IN MINING ENVIRONMENTS

geological structures below the surface [31]. Typical seismic imaging systems use a frequency up to 5 kHz from an active source such as an air gun or piezoelectric transducer. Such systems enable penetration up to 100 m, but are only capable of identifying large structures due to the low operational frequency [32]. A passive short-range seismic system was demonstrated, using the sound from a long wall shearer in a coal mine to penetrate the coal face and predict the roof structure and depth ahead of the shearer [33].

Ultrasound imaging has been used for over four decades to determine concrete strength and characteristics. This has developed into a growing field of research for Non-Destructive Testing (NDT) of concrete structures. The applications of NDT have grown to also include interrogation of structures to discover features, such as reinforcing steel bars, and faults within the concrete such as voids [34].

Ultrasound has been used in underground mining previously to examine roof rock bolts that are inserted into the rock to provide reinforcement. A successful application of ultrasound to testing the bolts in place of destructive removal techniques was by [35].

Using sound to interrogate the inside of an object also has many similarities to Ground Penetrating Radar (GPR). Ultrasonic and GPR analysis were applied to brick walls to determine the presence of voids within the structure [36]. Both methods were found to yield suitable results, and in fact, complemented each other in the resolution of void positioning. The authors in [37] applied a number of different ultrasound techniques and GPR to fabricated concrete structures with voids and other anomalies. Again, both ultrasound and GPR provided results suitable to extract information regarding the position of those voids and anomalies, although neither method was able to extract all anomalies.

The acoustic techniques mentioned require the transducers and ground to be ‘coupled’, where the transducer is placed in contact with the ground. In a medical setting, ultrasonic systems use a gel to assist coupling. The ore at the drawpoint has a very irregular surface making coupling all but impossible (see Figure 3). For this reason, an alternative imaging system was sought that allowed the image to be obtained in a stand-off arrangement, where there is an air gap between the sensors and the material.

**Ground Penetrating Radar** GPR provides the ability to observe features and objects beneath the surface of the rock pile using electromagnetic waves. As the signal propagates through the material it is reflected off interfaces in the material where the electrical characteristics change. Reflections can occur due to the presence of conductive materials or where the material changes, such as the presence of a void within the pile [38].
A time-domain GPR system uses an antenna to transmit a pulsed electromagnetic signal into the ground and the reflections from subsurface features are then received by either the same antenna (mono-static) or a separate antenna (bi-static). The receive antenna can be a single antenna, requiring a raster-pattern to achieve 2D or 3D data collection, or an array of antennas which capture a swath of information [39].

The main civilian uses of GPR are in archaeological discovery [40], non destructive testing [41] and engineering examination of soils [42]. GPR was used to detect tree root systems within soil [43]. Snow, water and ice content within glaciers has been examined using GPR [44, 45]. GPR has also been used to detect land mines [46].

Within the mining industry radar has been used for autonomous vision systems as it is able to penetrate dust stirred up by vehicle movements [47]. Fragments on a moving conveyor belt have previously been imaged using optical cameras, however dust and irregular lighting conditions can limit the effectiveness of the images obtained. High frequency radar which can penetrate dust and requires no additional lighting sources can be used for surface imaging of fragments to obtain fragmentation size distributions [48].

Penetrative radar was used to characterise rock responses in an underground mine [49]. In more recent times, [50] has achieved high resolution of coal seam horizon depth down to about 5 mm accuracy, allowing more efficient extraction of coal.

Rock fractures within an ore mass in underground mines could lead to rock burst, where the mine face fails violently. This situation is a danger to personnel working nearby. A GPR system, operated at 500 MHz, was used to image fractures up to approximately 8 m into the rock mass [51]. The images showed that preconditioning of the rock mass through deep blasting substantially reduces the likelihood of rock burst. The study also showed that GPR was an effective tool for short range imaging in an underground mine.

Waste rock from mines have been investigated to observe ground water movement within the voids [52, 53]. These surveys typically used a low frequency (∼ 200 MHz) to obtain images at depths of up to 10 m. Ground truths [54] were established for shallow features, and interpreted for deeper structures. Similarly, [55] used GPR to investigate rock pile stability of a mine. GPR was able to measure stratigraphic features down to a depth of about 5 m depending on conductivity and water characteristics.

GPR was an effective tool for measuring volumes of fragmented material [56]. Gravel stock piles were scanned using a commercial GPR unit. The bottom of the stock pile was identified by the contrast between the overburden and clay sub-base. A Global Positioning System (GPS) survey collected surface data which enabled volumes to be calculated.
Most research into GPR has focused on identifying an object situated within a homogeneous body. As an example [57] investigated the resolution of GPR in archaeological surveys, embedding concrete objects in a sand box. Similarly, [39] used GPR to identify small objects representing land mines. In both cases, the purpose of the GPR survey was to identify the object, rather than the surrounding material which had been uniformly packed around the objects.

These scenarios have specific features which benefit the use of GPR for imaging purposes. Either the object was highly reflective, or distinctively different from the surrounding media: it was layered, or a regular geometric shape. In this research, the object sought was a larger irregularly shaped rock made of the same material as the surrounding media.

Imaging fragmented material, where there is no apparent difference between the material of the object and the material of the background required a different approach to previous investigations. One difference that could be leveraged was that a rock pile is actually made up of rock and air. The rock/air interface is detected by GPR and is used in the non-destructive testing of concrete structures to detect voids which could lead to failure [36, 58]. The authors of [59] used GPR, in combination with laser surface scanning, for detecting anomalies within railway ballast, while [60] used scattering from voids within the railway ballast to detect fouling from clays and other fines which weaken the ballast structure.

Identifying rock fragments after blasting has a number of useful outcomes for the mining industry. GPR has been used to investigate fragmentation after blasting in an open cut mine to improve rock fragmentation through better blast design [61]. More recently, [62] used continuous wave radar to measure fragment size of airborne rocks after blasting.

In the underground mining application studied in this thesis, the objective was to identify a fragment which is surrounded by similar material. Experimental results investigating GPR resolution for archaeological studies was also able to detect different grain size accumulation as a result of excavation and placement of objects in a sand box [57].

**Summary** Ground Penetrating Radar resolves both the intrinsic and extrinsic problems associated with imaging using optical camera. GPR can penetrate below the surface of a rock pile, and is not affected by dust in the air. GPR has also been used successfully in the mining industry, and is capable of identifying individual fragments based on changes in the characteristics of the material.

Although acoustic imaging has been regularly employed by the mining and construction
industries, it has a number of features that have been shown to make it unsuitable to this application. The typical low frequency characteristics of seismic systems are insufficient to resolve small objects, and ultrasound systems are typically employed for short range imaging. Both acoustics systems however require close coupling between the transducers and the propagating medium, making them unsuitable for stand-off imaging applications.

2.2 GPR Image Acquisition

GPR images are typically collected by moving the antenna across the ground and capturing the reflections from subsurface features. The antenna system may consist of one or more transmit antennas and one or more receive antennas. For a ground coupled antenna system, the antennas are placed or moved together across the ground, and the signal recorded from reflections off sub-surface features, as depicted in the left of Figure 7. Regardless of the number of antennas used, this method captures signal reflections and relies on the signal travelling through the media twice.

An alternative method of signal capture is trans-illumination. This method places the antennas on opposing sides of the media, as shown in the right of Figure 7. In this case, the signal only travels once through the material, thus reducing signal losses.

The choice of these two methods depends on the physical nature of the survey. If the antennas are unable to be placed to permit trans-illumination, a reflection survey is the only available capture mode.

Figure 8 shows some of the paths a signal can take between the transmit (Tx) and receive (Rx) antennas. Energy is recorded from a direct air wave (path ’A’) that travels through the air between the antennas. Energy can also travel through the ground surface directly
2.2. **GPR IMAGE ACQUISITION**

Figure 8: The signal energy travels many paths between the transmit (Tx) and receive (Rx) antennas.

to the receive antenna (path ’B’). Within the ground medium, the signal may reflect off one (’C’) or between multiple objects (’D’) before it reaches the receive antenna.

The waveform received by an antenna at a single location is digitised into a trace, or A-scan, in the time domain. This trace is a recording of the electromagnetic wave energy that has propagated from the transmit antenna (Tx) to that specific receive antenna (Rx) and recorded [63]. The signal recorded includes the many reflections that arise from the path(s) the energy has travelled (see Figure 8).

Each trace can be thought of as a 1-dimensional recording of the signal at that location. Joining many spatially related traces, such as those recorded with a moving antenna structure, produces a 2-dimensional representation of the medium under investigation. A 2-D recording of subsurface features is called a B-scan. Similarly, arranging multiple spatially related B-scans can be used to construct a 3-D model, or C-scan, of the subsurface features.

### 2.2.1 Resolution

As stated above, in a typical GPR survey the signal received is the energy reflected from subsurface features. In order to identify individual objects within the material under investigation the relationship between the GPR operational characteristics and the achievable resolution must be understood.

The resolution achievable by a particular GPR system is effectively the minimum distance
between two objects such that each object can be detected individually, and is measurable in both the vertical and horizontal planes.

Radar is a ranging tool (RADAR stands for RAdio Detection And Ranging) where distances are measured to objects in units of time. In the temporal dimension, resolution is represented as a measurable difference in time between two objects. Thus, if the reflections from two objects can be identified separately in time, they can be resolved in distance.

The relationship between a signal and time for radar is established through bandwidth and pulse width. As can be seen in Figure 9, a reflection pulse has a defined width \( W \) which is measured at the half-height point. If two reflection pulses overlap, the sources will not be separately identifiable. If the two pulses are separated by more than \( W \), they will be able to be resolved as individual pulses. Pulse width reflects the bandwidth of the signal through the relationship [2]:

\[
W = \frac{1}{B}
\]  

(1)

The greater the bandwidth \( B \), the shorter the pulse width \( W \). Hence, higher bandwidth signals are able to resolve objects with smaller separation.
GPR systems are characterised by the bandwidth ($B$) of the signal and the centre frequency ($F_c$). A typical GPR has a $B : f_c$ ratio of at least 1. A GPR system with a 1.4 GHz centre frequency will commonly have a bandwidth of at least 1.4 GHz.

Both the horizontal ($\Delta l$) and vertical ($\Delta r$) resolution of a radar system can therefore be related to the signal bandwidth and pulse width of the signal. In the vertical dimension, the relationship is

$$\Delta r \geq \frac{Wv}{4} \quad (2)$$

and in the horizontal dimension

$$\Delta l \geq \sqrt{\frac{vdW}{2}} \quad (3)$$

where $v$ is the signal velocity and $d$ is the distance to the object.

Equations (2) and (3) show that the resolution achievable is a result of the radar system parameter $W$ and the velocity of the signal through the material $v$. Velocity, as will be discussed in Section 2.4, is a function of the materials electrical characteristics. In the horizontal dimension as objects get further from the antennas the distance between objects must be greater in order to resolve them.

Experimental results in [64] found that vertical resolution also depended on the composition of the reflectors. A higher conductivity in the nearer reflector could mask the second reflector, hence more distance would be required to resolve the second object. These experiments were conducted with air as the transmission media.

### 2.2.2 Coupling

In most cases, GPR antennas are placed in very close proximity to the ground to provide a good coupling between the ground and the antenna. This ensures that most of the energy will be transmitted into the ground and not reflected back off the surface, cluttering the received signal. Close coupling also has the effect of focusing the signal [65].

While it is normally desirable to achieve a close coupling between antenna and the ground surface, in some situations this is not possible.

As the antennas are elevated, the vertical separation between the antenna and object becomes larger compared to the horizontal separation between the antenna and object. This
decreases the resolution in the horizontal plane requiring a greater distance between objects to resolve them individually. In equation (3), as \( d \) (being the distance between the antenna and object) increases, so the minimum separation between objects (\( \Delta r \)) increases. One benefit of raising the antenna is that this also reduces the effect of objects located large distances horizontally from the antenna, thus improving contrast of objects located closer to the antenna centre [65].

Different distances between the antennas can assist with signal detection by focusing returns at defined depths. Focusing of signal returns can be achieved by adjusting the separation of the transmit and receive antennas. By varying the distance between the antennas, the reflections from specific depths can be improved compared to returns at other depths [66].

The largest problem from stand-off antennas is the effect of surface reflections cluttering the signal. As the antennas are elevated, less energy enters the ground, and more energy is reflected from surface features. Typically this can be removed by time gating the signal based on the elevation of the antennas [67]. To effectively remove surface clutter, it is important to know the true time zero position in the signal to correctly apply time gating.

### 2.2.3 Time Zero Determination

Time zero drift is the dominant cause of non-random errors in GPR data collection. Drift in the location of time zero in the recorded signal is caused by changing characteristics of the delicate electronics in the radar system as it is used. Manufacturers recommend a typical ‘warm-up’ period of approximately 10 minutes to allow the electronics to stabilise, reducing the effect of the drift in time zero.

As previously stated, radar is a ranging tool, measuring the time signals take to travel between an object and the radar antennas. In the ideal situation, this measured time would be an absolute measurement of the pulse arrival. Time zero drift, however, means the pulse will drift over time as the zero point drifts.

Time zero drift can be compensated for by using a time factor to negate this drift, allowing data to be repositioned in time which enables the absolute position of the signal characteristic to determine range [68]. While this method may correct errors in a single data collection following calibration, it does not permit the comparison of data from different collections without the additional recording of the time correction factor for all measurements across all data sets. Further, with multiple antenna pairs in simultaneous operation,
calibration across pairs would be complicated.

There are a number of possible positions for time zero in the received signal. While a commonly accepted position is the first positive peak of the direct wave, the use of a calibrated position provided consistent results for determining time zero [69].

In a typical bi-static antenna configuration, the receive antenna is located close to the transmit antenna, permitting the recording of the direct air wave in the signal. Given the proximity of the receive antenna to the transmit antenna, this gives a simple method of determining time zero in the receive signal based on the direct air wave and a calibrated position. This allows the range to an object to be interpreted relative to the received time zero, and avoids the need to record correction factors [70].

2.3 GPR Image Processing

Once the data has been captured, the next step is to interpret the data to identify features. Typically, a user will construct a 2D image of the data, however before an image can be interpreted, there are a number of steps that can be taken to improve the quality of the data to aid understanding.

A significant limitation of GPR is clutter. Due to the broad beamwidth of the GPR signal, reflections from objects within the beam other than the target, including those offset from the horizontal position of the antenna, are regarded as clutter. The primary goal of signal processing is to remove or reduce clutter from the GPR return signal [71].

2.3.1 Pre-Processing

There are a number of standard pre-processing steps that are normally carried out on A-scan GPR data.

If a number of traces are recorded at each physical location, a percentage of traces at the start and end of capture can be discarded to remove any effects from initiating or ceasing data collection (such as electrical jitter in switching) [72].

It is desirable that each radar A-scan will have a symmetric amplitude probability distribution about the mean. Any asymmetry can be removed by applying a zero-offset or DC removal process whereby the mean is subtracted from each sample point. This has the effect of centring the scan about zero amplitude [71].
2.3.2 Migration

As previously mentioned, most GPR systems use a broad beam antenna, detecting reflected energy from subsurface structures. Given the broad beamwidth, objects illuminated by the antenna pulse, including those offset horizontally from the antenna position, contribute to the received radar signal. Hence, the interpretation of a single time response is limited to the range of an object – no information regarding horizontal offset can be inferred from the signal [75].

At each surface position the antenna sends a pulse beam into the ground, and records the returning signal. The reflection of the radar energy from the object is detected by the antenna (see left of Figure 10). This beam is conically shaped, thus it not only detects objects located directly beneath the antenna, but also those objects offset from the horizontal position of the antenna.

As the antenna is moved across the surface, the range to the illuminated object also changes - firstly decreasing as the antenna approaches until the shortest range is recorded when the antenna is directly above the object. The range then increases as the antenna

Figure 10: GPR signal detects hidden objects such as reinforcement bar [3]

When the transmit and receive antennas are in close proximity, low frequency energy can contaminate data, particularly early in the time signature. This contamination of the signal is known as "wow". A pre-processing step called 'de-wow' will remove these components [73].

When there are differences in the coupling, which results in uneven energy propagation into the ground material, it is important to normalise the data to enable comparisons between data. The captured data can be normalised by scaling to a nominal value based on the direct wave energy recorded [74].
moves past and beyond the object. This change is depicted in B-scans as a hyperbola (see Figure 11).

Thus, in a 2D scan, the radar will detect an object before it is directly above the object, and continue to detect the same object after it has moved beyond its horizontal position. This produces the typical GPR hyperbolic signal as depicted in the right of Figure 10.

In Figure 11(a) the scan was recorded (synthetically) left to right, with the dominating features being the lower edges of the two objects. The hyperbolas are focused at about 6 ns, which represents the point in time where they are closest to the antenna. With the antenna in the start position (x = 0) the range to the lower edge of the left object appears in the first A-scan at about 7.5 ns. As the antenna nears the left object (horizontal position \(x \leq 0.3\) m) the ranging distance to the lower edge of the left object decreases. Then, as the antenna moves past the left object, the range to the lower edge is measured until the end of the scan is at about 12.5 ns.

Figure 11(a) also gives an example of the footprint that can be expected from a GPR antenna. As mentioned above, no horizontal information can be inferred from an A-scan. With the antenna located at position 2.0 m on the scan axis (extreme right), the left object (positioned at about 0.3 m to 0.7 m) is still visible in the scan at about 12.5 ns. It is this feature of GPR that makes interpreting images very difficult.

Figure 11(b) shows an A-scan through the left object along the dotted line. The effects of the broad beam can also be seen in the individual A-scan. The dominant features in the A-scan are peaks at about 3 ns and again at about 6 ns which are reflections from the top
and bottom of the objects respectively. There is another disturbance in the A-scan at about 9 ns which, without further a priori knowledge, might be interpreted as another object at a greater depth. By comparing this A-scan with the resulting B-scan (Figure 11(a)) this reflection can be identified as clutter from the right-hand object.

The hyperbolic structure is an unfocused depiction of the scatterer [76] which is removed using various migration processes. These are generally derived from seismic imaging research, and include the maximum convexity migration algorithm [39]. This algorithm works by comparing every sample point across the entire B-scan. Each sample point that falls on a curve of maximum convexity is considered to be a reflection from the same point, and can be removed [77]. Thus, knowing the propagation speed of the signal through the media, or assuming a constant speed as required by maximum convexity migration, we can remove the hyperbolas. In the case where the propagation speed is unknown, or the speed is variable, another method is required.

Objects within the field of view, but offset from the antenna, clutter the signal return from objects directly beneath the antenna. The hyperbolic structure also contributes to the clutter in an image by interfering with the signal return in adjacent traces. Removing surface clutter from images using time gating has the undesired effect of removing the reflections from shallow objects.

Averaging also works to remove coherent clutter, but is ineffective in heterogeneous material. Removal of incoherent clutter is based on a statistical knowledge of the background material, or the target. In heterogeneous material, these properties will vary. Using a priori knowledge of the target reflection [46] or shape [78] to build a reference signal is less useful when the target shape is unknown or irregular.

A new method has been devised to overcome these limitations [79] and will be discussed in Section 3.4.

### 2.4 Material Properties and Response

Fundamentally, the operation of ground penetrating radar is governed by the set of equations (4)–(7) known as Maxwell’s Equations. These equations describe how electrical and magnetic waves interact to produce a travelling wave through a medium.
2.4. MATERIAL PROPERTIES AND RESPONSE

Gauss’ law for electricity: \( \nabla \cdot D = \rho \) \hspace{1cm} (4)
Gauss’ law for magnetism: \( \nabla \cdot B = 0 \) \hspace{1cm} (5)
Faraday’s law of induction: \( \nabla \times E = -\frac{\partial B}{\partial t} \) \hspace{1cm} (6)
Ampere’s law: \( \nabla \times H = \frac{\partial D}{\partial t} + J \) \hspace{1cm} (7)

where
\( E \) is the electric field strength (V m\(^{-1}\))
\( H \) is the magnetic field strength (A m\(^{-1}\))
\( D \) is the electric flux density (C m\(^{-2}\))
\( B \) is the magnetic flux density (T)
\( J \) is the current density vector (A m\(^{-2}\))
\( \rho \) is the charge density (C m\(^{-3}\))

The medium through which the electromagnetic wave propagates affects the wave. The constituent relationships of permittivity (\( \epsilon \)), conductivity (\( \sigma \)) and permeability (\( \mu \)) represent the material parameters that affect the propagating signal. They are defined by the following relationships:

\[ D = \epsilon E \] \hspace{1cm} (8)
\[ J = \sigma E \] \hspace{1cm} (9)
\[ B = \mu H \] \hspace{1cm} (10)

where
\( \epsilon \) is the permittivity of the material (F m\(^{-1}\))
\( \sigma \) is the conductivity of the material (S m\(^{-1}\))
\( \mu \) is the permeability of the material (H m\(^{-1}\))

Changes in the propagation medium can be identified through changes in the signal by understanding the affect these properties have on the signal.
Permittivity  The Electric Permittivity ($\epsilon$) is a measure of the ability of the material to store energy from the electromagnetic wave. As the electromagnetic wave propagates through the material, the electric field displaces positive and negative charges from their original position. The displaced charge gives rise to their own electric field, which opposes the applied electric field. Two consequences of this, which will be discussed in the following sections, are that the signal is attenuated and that the velocity is slowed.

Permittivity is a complex quantity $\epsilon = \epsilon' - i\epsilon''$, but is usually referred to by its non-dimensional relative permittivity $\epsilon_r$

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}$$ (11)

where $\epsilon$ is the permittivity of the material in question, and $\epsilon_0$ is the permittivity of free space ($8.8542 \times 10^{-12}$ F m$^{-1}$).

The relative permittivity of a material is often called the "dielectric constant". Permittivity being complex does exhibit variability with frequency and it is the low frequency value of permittivity that is often referred to as the dielectric constant. For most GPR applications this scalar quantity for permittivity is sufficient for simple approximations [80].

Conductivity  The Electric Conductivity ($\sigma$) of the material affects the attenuation of the signal by converting energy to heat. In air, conductivity is essentially zero, so there is no (or negligible) loss of energy from the signal caused by the air.

At low frequencies conductivity can be considered a static quantity, $\sigma_s$ measured in Siemens/metre (S m$^{-1}$). Within earth materials and at higher frequencies conductivity must be considered a complex quantity $\sigma = \sigma' - i\sigma''$ which can affect the propagation of energy through the material. At GPR frequencies however, the imaginary component ($\sigma''$) is often insignificant, so conductivity can be simplified to its real component [81].

Permeability  Magnetic Permeability ($\mu$) relates to the magnetic effect of materials on the electromagnetic signal, and is only relevant in materials comprised of iron or other ferromagnetic materials. In most earth materials the permeability can be simplified to that of free space ($\mu_0 = 1.26 \times 10^{-6}$ H m$^{-1}$) [2].
2.4. MATERIAL PROPERTIES AND RESPONSE

2.4.1 Material Response

The material properties \((\epsilon, \sigma)\) affect the signal as it propagates through the material under investigation. In the time domain, these effects may be visible as amplitude attenuation and velocity dampening.

The frequency domain has been used to determine the electrical characteristics of soil [82] and concrete [73] by observing changes in the received spectrum.

As stated above, permittivity and conductivity are both complex quantities. The real part of permittivity \((\epsilon')\) and the imaginary part of conductivity \((\sigma'')\) both produce a current out-of-phase with the incident electric field. In contrast, the real part of conductivity \((\sigma')\) and the imaginary part of permittivity \((\epsilon'')\) produce an in-phase current. The terms of real effective permittivity \((\epsilon'_e)\) and real effective conductivity \((\sigma'_e)\) have been defined as [83]

\[
\epsilon'_e = \epsilon' - \frac{\sigma''}{\omega}
\]

and

\[
\sigma'_e = \sigma' + \omega\epsilon''
\]

where \(\omega\) is the angular frequency, \(2\pi f\), with \(f\) being the frequency in hertz. At GPR frequencies, it can be assumed that conductivity is frequency independent and \(\sigma'' = 0\), such that [84, 81]

\[
\epsilon'_e = \epsilon'
\]

In materials with a conductivity lower than \(10\ \text{mS m}^{-1}\) the effect of parameter \(\epsilon''\) can be neglected reducing the effective conductivity to [85]:

\[
\sigma'_e = \sigma'
\]

The velocity, \(v\), and attenuation, \(\alpha\), of the wave through a propagating material are given by [2]:

\[
v = \frac{c}{\sqrt{\mu'\epsilon' + \frac{c^2}{\sqrt{1 + tan^2\delta} + 1}}}
\]
\[
\alpha = \omega \sqrt{\mu \varepsilon} \left( \frac{1}{2} \left[ \sqrt{1 + \tan^2 \delta} - 1 \right] \right)^{\frac{1}{2}}
\]  
(17)

where

\[
tan\delta = \frac{\sigma_e}{\omega \varepsilon_e}
\]
(18)

When \( tan\delta \ll 1 \) and the wave passes through a non-ferrous medium the velocity can be approximated by equation (19) [86]:

\[
v = \frac{c}{\sqrt{\varepsilon_r}}
\]
(19)

**Velocity**  This simplification of the velocity function supports the findings of [87, 83] and others that permittivity is constant with frequency in low to medium loss material and, accordingly, velocity is independent of frequency. Further, the velocity equation (19) can be used to estimate the relative permittivity of the propagating material [88, 63, 89].

The relative permittivity of most earth materials lie in the range of 2–16, while fresh water has a relative permittivity of 81. The effect of water on earth materials is to increase permittivity, thereby decreasing velocity.

The thickness of road pavements have been examined using GPR by measuring the velocity of the signal through the pavement layers [90]. Velocity-permittivity measurements have also been used to measure water content in concrete [41] and the ratio of snow:water:ice in glacial fields [44].

Railroad ballast presents a similar problem to the mine detection problem under investigation in determining characteristics in a heavily fractured medium. GPR velocity analysis was used to map changes in permittivity between clean railroad ballast and fouled ballast where voids were filled with wet clay sediments [91].

**Reflection Coefficients**  To measure permittivity with velocity measurements, it is important to know the actual distance the signal has travelled through the medium so that the velocity can be calculated. In the case of layered material, the distance through each layer may be unknown or variable. In such situations, the permittivity of each layer cannot be determined by velocity calculations unless destructive testing of the material can reveal the relevant thickness of each layer.
Relative permittivity can also be measured by the amplitude reflection coefficient of each layer. If the relative permittivity of the overlying layer is known, the relative permittivity for the underlying layer can be determined from the amplitude reflection coefficient. In the case of the top layer of a material, the overlying material is air, with a relative permittivity $\varepsilon_r = 1$.

The peak reflection amplitude of the incident wave, $A_{inc}$, is first measured using a Perfect Electric Conductor (PEC) located at the same range as the material under test [92, 93]. The peak reflection amplitude from the surface, $A_{ref}$, is then measured, and the reflection amplitude coefficient $\varepsilon_r$ measured using equation (20).

$$\varepsilon_r = \frac{(A_{inc} + A_{ref})^2}{(A_{inc} - A_{ref})^2}$$  (20)

Once the upper layer of the material is known, subsequent layers in the structure can be determined by continuing to apply equation (20) [94].

**Attenuation**  The changes in the peak amplitude of the reflections are caused by attenuation of the signal, according to equation (17). As the signal propagates through the medium, signal energy is lost within the medium, leading to lower amplitude values. Total losses as measured by signal attenuation are a composite of losses from a number of factors, including antenna loss, signal spreading, target scattering and material loss.

Attenuation can be measured in the time domain by measuring the change in the peak amplitude values at specific locations in time. Total losses can be measured using peak signal amplitudes through [71]

$$\text{Attenuation (dB)} = 20 \log \left( \frac{V_1}{V_2} \right)$$  (21)

A GPR time domain signal can be related to depth through velocity and permittivity calculations as outlined above. The density of road pavement layers has been measured using the attenuation of a GPR reflective signal. Through the application of specific mixture models (see Section 2.4.1) the density of real road pavements was able to be predicted in laboratory experiments [95]. Given the layered nature of the road materials, it is straightforward to establish the position of the different layers of the road in the time domain, determine the attenuation and, thus, the bulk density of the layered material.
Signal Energy  Attenuation can also be measured in the frequency domain as the reduction in signal energy [96]. While the time domain shows how a signal varies with time, in the frequency domain we can see how the signal energy is distributed over a range of frequencies. Parseval’s Theorem [97] shows that the energy in a signal is constant whether it is measured in the time domain or frequency domain as given by equation (22):

$$\sum_{n=0}^{N-1} |x(n)|^2 = \frac{1}{N} \sum_{k=0}^{N-1} |X(k)|^2$$  \hspace{1cm} (22)$$

As the signal propagates, energy is lost across the entire spectrum, and the spectral energy in a signal is calculated using equation (23)

$$E = \sum |X(f)|^2$$  \hspace{1cm} (23)$$

where $X(f)$ is the Discrete Fourier Transform (DFT) of the time domain signal $x(n)$, and the DFT function employed normalises the transform over length $N$ (see Appendix A). This equation will allow comparison of discrete data collected with the same sample rate. The frequency range can be bandwidth limited to a specific range of frequencies where the signal energy is concentrated. The attenuation of the signal in the frequency domain is calculated by

$$\text{Attenuation (dB)} = 10 \log \left( \frac{E_1}{E_2} \right)$$  \hspace{1cm} (24)$$

where $E_1$ is the signal energy from the direct wave before propagation and $E_2$ is the signal energy after propagating through the medium.

Quality Factor – $Q$  Due to the frequency dependence of material attenuation as described in equation (17), higher frequency components attenuate more than lower frequency components. This is evidenced by a shift in the peak frequency to a lower part of the spectrum. By measuring this shift we can estimate the attenuation as the signal propagates through the medium.

A parameter $Q$ which describes the attenuation of the signal has been defined by [83]. It was found that attenuation was an approximately linear constant throughout the GPR frequency band, and $Q$ describes the slope of the attenuation versus frequency curve. Ground materials were found to exhibit $Q$ values in the range of 2–30, where smaller values were associated with higher loss.
2.4. MATERIAL PROPERTIES AND RESPONSE

$Q$ is closely related to $\tan\delta$ (see equation (18)) through the relationship

$$Q = \frac{1}{\tan\delta}$$  \hspace{1cm} (25)

which confirms the relationship described above, that large $Q$ values suggest lower energy loss [98].

As stated above, $Q$ describes the loss over the frequency band, and in particular, the rate at which higher frequencies attenuate compared to lower frequencies. The result of this is a downshift in the frequency spectrum after propagating through the medium.

A number of methods for measuring $Q$ have been proposed. Using pulse-width measurements [83] measured $Q$ in GPR data. Measuring $Q$ with seismic data using the centroid frequency downshift was first proposed by [99]. The centroid of the frequency spectrum for the source and receive waves are determined as

$$f_s = \frac{\Sigma fS(f)}{\Sigma S(f)}$$ \hspace{1cm} (26)

$$f_r = \frac{\Sigma fR(f)}{\Sigma R(f)}$$

where $f_s$ and $f_r$ are the centroid of the source and receive wave respectively, $f$ is the frequency bin from the Fourier Transform and $S(f)$ and $R(f)$ are the absolute magnitude for respective frequency for the source and receive wave respectively.

The variance of each wave can be calculated

$$\sigma^2 = \frac{\Sigma(f_m - f)^2 S(f)}{\Sigma S(f)}$$ \hspace{1cm} (27)

where $f_m$ is the mean frequency of the range. $Q$ can then be estimated by

$$Q = -\sigma^2 \pi \left( \frac{\Delta f}{\Delta t} \right)$$ \hspace{1cm} (28)

where $\Delta f = f_s - f_r$ and $\Delta t$ is the signal travel time between the two wavelets. This method has been applied to GPR data [100, 84].

Using a similar method to [101], [102] extracted wavelets from the time domain surrounding specific horizons in the subsurface signal. After manually identifying horizons in the
time domain signal of reflection data, a window of data was extracted between each horizon, producing an average value over the depth of the horizon. \( Q \) was estimated using the spectral maximum \( \omega_t \) of the wavelet spectrum at time \( t \) compared to the reference frequency \( \omega_0 \) using equation (29)

\[
\frac{1}{Q} = 4 \frac{\left( \omega_0^2 - \omega_t^2 \right)}{t \omega_0^2 \omega_t} \tag{29}
\]

Scattering can result in frequency dependent attenuation that is similar to the intrinsic attenuation measured by \( Q \) [102]. Hence, attenuation measured in the field is the combined effect of scattering and intrinsic attenuation.

### Mixture Models

The material properties described above suggest a simple, uniform material represents the propagating medium. Of course, the nature of earth materials is that the material under test is likely to be a complex, heterogeneous material composed of a number of different components.

In application examples referenced above, such as the road pavement examinations using GPR, the material was composed of multiple layers, each comprising a number of materials with their own specific electrical characteristics.

The **Complex Refractive Index Model** (CRIM) (equation (30)) and the Landau and Lifshitz, Looyenga model (LLL) (equation (31)) are standard volumetric models based on fractional volumes which allow material parameters to be considered as composite, rather than having to treat each specific material individually.

\[
\epsilon_s = \left( \frac{\sqrt{\epsilon_m} + V_m - 1}{V_m} \right)^2 \tag{30}
\]

\[
\epsilon_s = \left( \frac{\sqrt[3]{\epsilon_m} + V_m - 1}{V_m} \right)^3 \tag{31}
\]

For a two-phase material of air-solid mixture, (30) and (31) (both as reported in [103]) predicted the complex permittivity of the solid component, \( \epsilon_s \), where \( \epsilon_m \) is the complex permittivity of the mixture. The volume fraction \( V_m = \rho_m/\rho_s \) of the solid material in the mixture was derived from the known density of both the solid (\( \rho_s \)) and the mixture (\( \rho_m \)). When used on the real part of the complex permittivity, both CRIM and LLL
2.5. SUMMARY

mixture models were found to be consistent with the bulk density of pulverised coal and air mixture [104].

The relationship between relative permittivity and bulk density was found to be linear when using a CRIM or LLL model [104]. The linear relationship of the density with the real part of the complex permittivity allows extrapolation to the solid material. In order to use these relationships, the bulk density of the mixture (air-particle mixture density) and the specific gravity or density of the solid material needs to be known.

To determine the relative permittivity of a mixed sample, given the relative permittivity ($\epsilon_s$) and density ($\rho_s$) of the solid material, and bulk density of the sample ($\rho_m$), [104] found equivalent representations of the linearity between the square root (equation (32)) and the cube root (equation (33)) of the relative permittivity of a sample material with its bulk density. Given the relative permittivity ($\epsilon_s$) and density ($\rho_s$) of the solid material, and bulk density of the sample ($\rho_m$), [104] found a linearity between the square root (equation (32)) and the cube root (equation (33)) of the relative permittivity of a sample material with its bulk density.

\[
\sqrt{\epsilon_m} = \frac{\sqrt{\epsilon_s^2 - 1}}{\rho_s} \rho_m + 1 \tag{32}
\]

\[
\sqrt[3]{\epsilon_m} = \frac{\sqrt[3]{\epsilon_s^2 - 1}}{\rho_s} \rho_m + 1 \tag{33}
\]

2.5 Summary

This chapter has reviewed computer imaging systems that are currently being used in the mining industry for a candidate system to solve the research questions identified in Chapter 1. While optical cameras are common, and would augment current and future practices, they suffer from being a surface imaging tool only. Although acoustic imaging techniques are able to penetrate deeply through the earth material, they were dismissed due to the coupling demands and low resolution of the resulting images.

Ground penetrating radar is a suitable candidate system as it has been used successfully in the mining industry for other applications. There are also examples of similar imaging applications where GPR has been used successfully.

This chapter has identified two possible techniques that could be applied to the research questions posed in Chapter 1. Firstly, it will be shown in Chapter 3 that GPR is a capable
and mature method of producing 2D and 3D representations of the subsurface structure. Reflections arising from changes in the electrical characteristics of the subsurface structure could allow interpretation on whether an oversized fragment is present. The rock pile is comprised of ore and air pockets, and reflections will arise from the boundary between rock and air. Analysis of the resulting images will identify areas where there are many reflections, indicating smaller fragments, and areas where there are no reflections in the image, which may indicate a large fragment.

Secondly, the particular characteristics of the volume can be examined by GPR signal analysis. By measuring the effect of the material characteristics upon the signal, details about the composition of the ore volume can be deduced. Chapter 4 will present investigations of volumetric methods on small samples. As will be shown in Chapter 5, similar methods will be employed on a medium scale model of a drawpoint and can be used to predict the presence of a large rock in the rock pile.
Chapter 3

Imaging Inside the Rock Pile

The typical use for a Ground Penetrating Radar (GPR) system is to image the subsurface to allow identification of features within the ground. As described in Section 2.1.2, GPR has been used to image archaeological structures, tree roots and engineering infrastructure beneath the ground. In this chapter, the use of a commercial GPR system to image rock piles will be explored.

A standard GPR survey is undertaken by scanning an area with the antenna closely coupled to the ground. Reflections from changes in the electrical characteristics of the ground material are recorded as an individual trace (an A-scan). A series of A-scans are typically displayed as a 2-D image (B-scan) formed along the scan line. In turn, B-scans can be joined to form a 3-D image (C-scan). The image obtained for interpretation is directly dependent on the GPR system performance characteristics and the material characteristics of the ground material.

The first part of the chapter will establish preliminary material characteristics for the ore under test (Section 3.1). The radar system operation and performance capabilities will be described in Section 3.2. Experimental results of rock pile imaging will be presented in Section 3.3. Section 3.4 presents a new algorithm to reduce clutter in GPR images. This research has been published in [105], [106] and [107].

The main purpose of this study is to design a system capable of assisting an underground mining operation as described in Chapter 1. The results of rock pile imaging will be assessed in this context in Section 3.5.
3.1 Preliminary Material Characteristics

This research is concerned with investigating rock material from a porphyry copper deposit bearing approximately $1 \text{g t}^{-1}$ gold and 0.38% copper. After explosive and hydrofracturing, the ore is presented at the draw point for collection, with sizes ranging from small ($<25 \text{mm}$) to very large ($>1 \text{m}^3$). It is the detection of these very large fragments that is of interest.

The first phase of experimental work was to establish the radar system parameters and material parameters. The material characteristics can essentially be divided into two components - solid rock and an air/fragmented rock combination.

Approximately 20t of ore samples were obtained from the mine. The ore supplied included many contaminants such as small pieces of concrete, steel and plastic reinforcing fibres. The material was manually sifted to provide samples of uniform rock fragment sizes and enabled the removal of contaminants.

As discussed in Chapter 2, the primary parameters affecting radar signal propagation through rock is the permittivity and conductivity. Section 2.4 defined real effective permittivity ($\epsilon'_e$) and real effective conductivity ($\sigma'_e$) for low loss materials (where $\sigma < 0.010 \text{S m}^{-1}$) as

$$\epsilon'_e = \epsilon'$$  \hspace{1cm} (34)

and

$$\sigma'_e = \sigma'$$  \hspace{1cm} (35)

The DC component of conductivity was measured as $\sigma' = 0.003 \text{S m}$ [108]. Section 2.4.1 also demonstrated that if the loss tangent $\tan\delta \ll 1$ the velocity equation reduces to equation (36).

$$v = \frac{c}{\sqrt{\epsilon_r}}$$  \hspace{1cm} (36)

This allows a simplified measure of permittivity based on the signal velocity through the rock material. For the ore under test $\tan\delta$ can be calculated according to equation (18) as
3.2. THE RADAR SYSTEM

The radar system used in the experiments was a SiroPulseII Ground Penetrating Radar system, shown in Figure 12, manufactured by CSIRO (Australia) and purchased in late 2010. The antenna unit is housed in a plastic material, and features three wheels on the underside for easy motion across a smooth surface. The wheels elevate the antenna unit approximately 10 mm above the ground. Each antenna unit features three separate antennas - the centre antenna is for transmission, the outer two antennas for receiving the reflected signal, one of which is 180° out of phase.

\[
\tan \delta = \frac{\sigma'}{\omega \varepsilon'} = \frac{0.003}{2\pi f \varepsilon_r \varepsilon_0} = 0.004
\]

and 0.004 \( \ll 1 \)

This shows that the simplified velocity function holds for permittivity measurements.

Figure 12: SiroPulseII GPR System
3.2.1 Calibration

Data was captured under three conditions using a stationary antenna, as described below. The analysis of that data (Sections 3.2.2 and 3.2.3) was confirmed by the equipment manufacturer in personal communication [109].

Scenario 1: each antenna was taken outside the building and a scan recorded by pointing the antenna to a clear area of the sky. The intention of this test was to record a signal with no reflection content.

Scenario 2: The antennas were then suspended from a beam and pointed downward, approximately 750 mm above a sheet of aluminium measuring 600 mm x 600 mm. The scan allowed a clean recording of the reflection from a perfect electrical conductor with no interference from nearby objects.

Scenario 3: The final scans were obtained with the antenna at rest on a large fragment of rock. The face of the rock was nearly smooth thereby allowing a close coupling of the antenna to the rock.

The captured data was then pre-processed to provide four separate data sets, as described below.

Air - the entire data scan from Scenario 1 above.

Alum - The reflection from the aluminium, Scenario 2, was isolated in the scan with a zero amplitude lead in and lead out.

Direct - the direct recording of the signal between the transmit and receive antennas was isolated from Scenario 2 with zero amplitude lead-in and lead-out.

Rock - the entire scan from Scenario 3

The data was then processed in the following manner, as previously described in Section 2.3.1 before further analysis of the signal in the time and frequency domains. See Appendix A for code listing.

1. raw data captured with the GPR system;

2. data imported into Octave/Matlab using the program scripts provided by CSIRO;
3.2. **THE RADAR SYSTEM**

Figure 13: Processed trace response for 800 MHz antenna showing **Air**, **Direct**, **Alum** and **Rock** response.

3. data was reduced to a single scan by removing the first and last 25% of scans, then averaging over the centre 50% of scans;

4. the DC was removed from the single scan;

5. low frequency components were removed (dewow) (see Section 2.3.1).

### 3.2.2 Time Domain

Figures 13, 14 and 15 show the processed trace response for the 800 MHz, 1400 MHz and 2000 MHz antennas. Each figure shows the response to each of the four data sets **Air**, **Direct**, **Alum** and **Rock**.

The **Direct** signal was effectively a match for the signal in **Air** up to about 1.5 ns. The direct signal was trimmed of any responses after returning to zero at approximately 3 ns. The reflection from the aluminium plate (**Alum**) was also trimmed leading up to the reflection and after the reflection returns to zero.

Perhaps the most interesting response was the **Rock** signal. The initial direct signal between the transmit and receive antennas was altered by the rock, and the signal through the rock disappeared very quickly through the trace.
CHAPTER 3. IMAGING INSIDE THE ROCK PILE

Figure 14: Processed trace response for 1400 MHz antenna showing Air, Direct, Alum and Rock response.

Figure 15: Processed trace response for 2000 MHz antenna showing Air, Direct, Alum and Rock response.
3.2. THE RADAR SYSTEM

Figure 16: Positive signal envelope for the 800 MHz antenna.

Table 1: SiroPulseII pulse width for each antenna at 3dB

<table>
<thead>
<tr>
<th>Antenna (MHz)</th>
<th>Air (ns)</th>
<th>Direct (ns)</th>
<th>Alum (ns)</th>
<th>Rock (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0.843</td>
<td>0.835</td>
<td>0.620</td>
<td>1.437</td>
</tr>
<tr>
<td>1400</td>
<td>0.608</td>
<td>0.605</td>
<td>0.426</td>
<td>1.101</td>
</tr>
<tr>
<td>2000</td>
<td>0.406</td>
<td>0.400</td>
<td>0.356</td>
<td>0.901</td>
</tr>
</tbody>
</table>

The scans recorded for Air, Direct and Alum were air coupled (\(\varepsilon_r \approx 1\)). Using signal velocity to calculate relative permittivity as described in Section 2.4 and equation (36), the Rock scan had a medium with a relative permittivity of \(\varepsilon_r \approx 9.7\).

Figures 16, 17 and 18 show the positive envelopes for each antenna by signal origin. The signal was scaled to a peak amplitude of '1' allowing the pulse width to be read at half amplitude. Table 1 shows the pulse widths for each antenna within each medium.

The pulse widths for each antenna were similar for Air and the Direct signal. For all three antennas the pulse width greatly increased when in rock. This is expected, due to the higher relative permittivity of the rock, and hence, the signal velocity being slowed by the media. This allows an examination of the pulse widths of the signals for each antenna under the same scan. Comparing the three positive envelope figures, it is evident the pulse
Figure 17: Positive signal envelope for the 1400 MHz antenna.

Figure 18: Positive signal envelope for the 2000 MHz antenna.
### 3.2. THE RADAR SYSTEM

#### Table 2: SiroPulseII bandwidth

<table>
<thead>
<tr>
<th>Antenna (MHz)</th>
<th>Air (MHz)</th>
<th>Direct (MHz)</th>
<th>Alum (MHz)</th>
<th>Rock (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>1186</td>
<td>1198</td>
<td>1613</td>
<td>696</td>
</tr>
<tr>
<td>1400</td>
<td>1645</td>
<td>1653</td>
<td>2348</td>
<td>908</td>
</tr>
<tr>
<td>2000</td>
<td>2463</td>
<td>2500</td>
<td>2809</td>
<td>1110</td>
</tr>
</tbody>
</table>

width of the 800 MHz antenna (Figure 16) is wider than the 1400 MHz antenna (Figure 17), which in turn is wider than the 2000 MHz antenna (Figure 18). For example, the pulse width of the signal in **Air** from Table 1, shows the 800 MHz, 1400 MHz and 2000 MHz antennas were 0.843 ns, 0.608 ns, 0.406 ns, respectively. Similarly, in **Rock**, the pulse widths were 1.437 ns, 1.101 ns and 0.901 ns respectively.

System bandwidth, as discussed in Section 2.2.1 (equation (1)) is defined as the inverse of the pulse width [2]

\[
B = \frac{1}{W}
\]  

(37)

where \(B\) is the system bandwidth in Hz and \(W\) is the pulse width in seconds. Based on Equation (37) the system bandwidth for the antennas are shown in Table 2.

As a comparison to other antennas reported in the literature, Reference [110] using a Mala Geoscience 500 MHz antenna, recorded a bandwidth of the reflection from a perfect electric conductor (Alum) at 340 MHz. Reference [111] recorded the bandwidth for an 800 MHz antenna at 770 MHz and a 1000 MHz antenna at 710 MHz. These readings, shown in Table 3 demonstrate that the ratio of bandwidth to centre frequency for the SiroPulseII are much greater than the ratios for the Mala Geoscience systems as reported.

#### 3.2.3 Frequency Domain Analysis

Figures 19, 20 and 21 show the frequency spectrum for each SiroPulseII antenna over the capture scenario described above. From these figures it can be seen that the response from the **Air** and **Direct** signals are, as for pulse width above, almost identical.

These measured bandwidth for each antenna agree with the system bandwidth calculations from Section 3.2.2 (Equation (37)) and have been confirmed through correspondence with the manufacturer [109].
### Table 3: Comparison of radar system bandwidths

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Direct (B)(MHz)</th>
<th>Alum (B)(MHZ)</th>
<th>Ratio $\frac{B}{f_c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiroPulseII 800 MHz</td>
<td>1198</td>
<td>1613</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>1653</td>
<td>2347</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>2809</td>
<td>1.41</td>
</tr>
<tr>
<td>Mala Geoscience 500 MHz</td>
<td></td>
<td>340 [110]</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>770 [111]</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>710 [111]</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Figure 19: Frequency comparison for the SiroPulseII 800 MHz antenna.
3.2. THE RADAR SYSTEM

Figure 20: Frequency comparison for the SiroPulseII 1400 MHz antenna.

Figure 21: Frequency comparison for the SiroPulseII 2000 MHz antenna.


Figure 22: Preliminary scan through a very small rock pile containing a large rock. Reflections are evident from the rubble (ovals), but appear absent from within the large fragment (hexagon).

### 3.3 Time Domain Imaging

Section 3.2 demonstrated that the rock from the mine did affect the radar signal. Preliminary material characteristics have estimated the relative permittivity using velocity calculations (as described in Section 2.4) which confirms the contrast between the rock ($\epsilon_r \approx 9.7$) and the air ($\epsilon_r = 1$) should ensure reflections arise from the interface between rock and air in the mixture. This contrast will allow an image of the inside of the rock pile to be generated.

Preliminary scans taken through very small samples (< 20 kg of rock) demonstrated that the radar signal was able to penetrate the rock, and also provided some evidence that the inner structure of a very small rock pile could be imaged [105]. Figure 22 shows reflections arising from within the rubble section of the pile, but an absence of reflections from the solid fragment.

Larger samples were created by placing fragmented rock into plastic crates, as shown in Figure 23. Samples containing gravel-sized fragments, or rubble, were compared to samples containing a larger fragment (approximately 250 mm in diameter) buried in the rubble.

Figure 24 shows two B-scans through separate crates containing ore fragments from the mine. The left image is over a crate containing only gravel-sized fragments. The right image is over a crate containing a large fragment embedded in the same gravel-sized fragments.
3.3. TIME DOMAIN IMAGING

Figure 23: Scan acquisition over a plastic crate containing rubble. The aluminium plate beneath provide clear reflections indicating the bottom of the rock sample.

Figure 24: Scans through a plastic crate containing rubble only (left) and a rock surrounded by rubble (right).
CHAPTER 3. IMAGING INSIDE THE ROCK PILE

The vertical axis of the images represent sample numbers from the data acquisition. The horizontal axis is the A-scan number, and approximates the horizontal distance over the physical scan dimension of about 1100 mm (left image) and 1000 mm (right image).

The surface of the rock pile, labelled ‘A’ in Figure 24, is apparent in both scans at about sample 50, near the top of the image. The crates were sitting on an aluminium plate, ensuring a good reflection from the bottom of the rock pile. This plate is identified as ‘B’ in both images at about sample 200 on the left and right sides of both images. The appearance of the plate on the sides of the image is from the antenna starting over the plate on the left of the image, then passing over the crate, and finally recording the plate through air on the right side of the image. The recording of the plate in early traces (0 – 50 horiz. axis) and late traces (500 – 550 horiz. axis) is through air, hence, it appears early in the trace (vert.). Once the antenna is completely over the crate, the signal must travel through the rock and so the plate appears much later in the scan at ‘D’ and ‘E’ in the image, at about sample 300-350 (vert.).

In the left image, with gravel-sized rubble only, there are internal reflections ‘C’ through out the image and until the aluminium plate/bottom of the box is observed ‘D’. In the right image, with the larger fragment, there are significantly less reflections noticeable from within the pile, particularly in the central region from sample 200-350. This suggests that there are no reflections arising from within the large fragment. The image is not particularly clear however, as clutter from surrounding rocks affect the signal in the time domain where the larger fragment is positioned.

The bottom of the box appears out of focus due to the multipath reflections from the plate interacting with the rubble. It is noticeable though that the appearance of the plate is much later in the scan through the rock at ‘E’, compared with rubble only ‘D’. This slowing of the signal velocity is caused by the higher permittivity of the solid rock.

While the images were processed to remove the hyperbola, as described in Section 2.3.2, the migration algorithms were unable to remove reflections from offset objects which occurred at the same point in time as reflections from objects beneath the antenna. This clutter obscures the larger fragment in the right of Figure 24, and also contributes to the loss of focus of the bottom of the box in the left image. A method to simulate a narrow beam width would be desirable to reduce the effect of this clutter.
3.4 Improving Time Domain Images

Chapter 2 discussed how the recorded signal energy comes from many reflection sources, cluttering the signal and resulting images. A typical artefact of this are the hyperbolas which affects scanning radar units and was demonstrated in Section 2.3.2. Filtering data to achieve a clean image of the object is the goal of signal processing.

The previous section also provides examples of scans through rock piles which showed it is possible to observe large fragments in a GPR image due to the lack of reflections originating inside larger rocks. However, lateral reflections clutter the image and these are not removed using standard migration techniques. A method to remove these lateral reflections would assist with cleaning the image to aid interpretation.

Figure 25(a) shows a simulated B-scan of two objects ($\epsilon_r = 3.5$) located in free space ($\epsilon_0$) and Figure 25(b) shows a simulated A-scan trace along the dotted vertical line drawn in Figure 25(a) (at about 0.5 m along the scan axis). The change in signal amplitude at 2.67 ns identifies the top of the box. Another signal change at 5.27 ns identifies the bottom of the box.
In a simulated GPR scan, *a priori* knowledge of the position of the object allows the confirmation of the vertical position of the object in the A-scan. In a measured GPR scan, this knowledge is not available, therefore there cannot be certainty that the two peaks were return signals from the same object, or in fact, may indicate a separate object within the field of view of the antenna.

In material with a known constant velocity, the depth $z$ from emitter to reflector is given by

$$z = \frac{vt}{2}$$  \hspace{1cm} (38)

where $v$ is the velocity of the signal through the material and $t$ is the measured time to the reflector. The typical hyperbolic pattern of a point reflector in motion across a B-scan is given by equation (39) (from reference [71])

$$z_i = \sqrt{(x_i - x_0)^2 + z_0^2}$$  \hspace{1cm} (39)

Ideally, the emitted radar energy would be a pencil-thin beam to illuminate only those objects directly beneath the antenna. The radar beam is, however, a wide beam. If the spatial origin of the reflection return could be identified, the return signal could be filtered to remove those lateral reflection sources. With a single radar source, the lateral offset position cannot be determined, and so equation (39) remains as a range equation. However, if a trace is recorded, and the antenna moved some distance $h$ along the signal propagation path (that is, away from the ground) it is expected objects that are located directly beneath the antenna to also move $h$ in the trace, such that

$$z_i = (z_0 + h)$$  \hspace{1cm} (40)

Equation (39) thus becomes

$$z_i = \sqrt{(x_i - x_0)^2 + (z_0 + h)^2}$$  \hspace{1cm} (41)

such that if $z_i \neq (z_0 + h)$ then the point reflector is not located on the signal propagation path and $z_i$ can be clipped from the trace. Thus, the trace data will only identify objects directly beneath the antenna. Whilst not determining the lateral offset to objects, the result is to exclude those objects clearly not located directly beneath the antenna. A new method
3.4. IMPROVING TIME DOMAIN IMAGES

called the Vertical Offset Filter (VOF) was developed [107]:

\[
\text{foreach } A-\text{Scan } x_i \text{ do}
\]
\[
\quad \text{foreach Offset A-Scan } x_{i,k} \text{ do}
\]
\[
\quad \quad \text{forall the Sample Values } z_{i,k} \text{ do}
\]
\[
\quad \quad \quad \text{if } z_{i,k} \text{ is a signal peak then}
\]
\[
\quad \quad \quad \quad s_{i,k} = 1;
\]
\[
\quad \quad \quad \text{else}
\]
\[
\quad \quad \quad \quad s_{i,k} = 0;
\]
\[
\quad \quad \text{end}
\]
\[
\quad \text{end}
\]
\[
\text{Align } k \text{ scans by vertical offset } h;
\]
\[
\quad z_i = \sum_{k=1}^{m} s_{i,k};
\]
\[
\text{if } z_i == m \text{ then}
\]
\[
\quad z_i = 1 \text{ //keep common signal peak;}
\]
\[
\text{else}
\]
\[
\quad z_i = 0 \text{ //discard signal peak;}
\]
\[
\text{end}
\]

\textbf{Algorithm 1:} The Vertical Offset Filter (VOF) algorithm.

The VOF improves the maximum convexity migration method by working only on individual A-scans, rather than the entire B-scan data. This reduces the computational cost to a 1-D processing method, while also allowing construction of clearer B-scans or C-scans. The novel method employed to achieve this improvement is the vertical offset obtained from the physical motion of the radar antenna, thus allowing the filter to remove all signal movements not matching the physical movement. This method does not require \textit{a priori} knowledge of the propagation speed, or the location of the target, in order to remove clutter. The algorithm exploits the fact that the wave shape flattens as the antenna is elevated, as reported in [65].

The algorithm requires a data set comprised of multiple A-scans collected at the same surface position \(x_0\). Each A-scan is offset in the vertical direction, that is, along the line of signal propagation by some distance \(h\).

For each A-scan in the data set, the signal is adjusted for the vertical offset distance \(h\). Signal peaks in each A-scan are identified as local \textit{maxima} and used to create a binary mask. Following a summation over all the binary masks, those signal peaks that do not
occur at the same time in each A-scan are excluded. The resulting mask is a binary mask of common signal peaks across each of the subject A-scans in the set of A-scans recorded at a distinct position.

Focusing GPR data using standard migration techniques requires the capture of B-scans or C-scans prior to migration processing. The VOF algorithm operates on A-scans and, as long as the antenna is moved perpendicular to the ground, could operate in real-time to remove these artefacts.

Figure 26 shows three individual (simulated) traces recorded at the same surface position. Each trace was aligned in the vertical plane to allow for the vertical offset at the time of recording. The alignment offset was calculated for each A-scan using corresponding peaks in the data set.

The set of traces was then examined, and positive peaks that occurred in each trace were retained, while those that did not occur at the same relative time in each trace were discarded. For example, in Figure 26, common peaks were identified at positions A and B, as indicated by the horizontal lines. Non-stationary signal peaks were evidenced by identifying movement within the time domain, shown by the slightly sloped line C and more pronounced slope of line D indicating a decline and an incline, respectively. By removing these non-stationary signals only the stationary signals remain, which corresponds to those features located immediately below the antenna.

### 3.4.1 Synthetic Results

To demonstrate the algorithm, a GPR scan was synthesised using MatGPR [112]. The environment described was a 2.0 m wide by 1.0 m deep scan area of free space ($v = 0.29979 \, \text{m s}^{-1}$). The space contained two objects of dimension 0.2 m x 0.2 m located at a depth of 0.4 m with a relative permittivity value $\varepsilon_r = 3.5$. Synthetic scans were produced using a (FDTD) 2D method simulating a 1200 MHz antenna.

In total, three synthetic scans were simulated over the same surface path, each with a different vertical offset. The 0.00 m offset represented the initial position of the antenna. The 0.15 m and 0.30 m vertical offsets were chosen arbitrarily.

Figure 25 (shown previously in Section 2.3.2) shows the raw GPR data obtained and presented as (a) a B-scan and (b) an A-scan through the centre of the left-hand object (represented in the B-scan as a dotted line). Although a very simple simulation, the images show the hyperbola from the top and bottom of the objects. It is also apparent that the
3.4. IMPROVING TIME DOMAIN IMAGES

Figure 26: Individual traces recorded at the same location with a vertical offset highlighting the non-stationary data
Figure 27: A simulated scan through an object: (a) shows the raw synthetic data with the object outline superimposed upon the scan, (b) after operation of the VOF with the object superimposed, and (c) after the VOF without the outline of the object.

A hyperbola of the right-hand object also appears beneath the left-hand object. Hence, the A-scan through the left-hand object contains signal response from the right-hand object.

Figure 27(a) shows a section from Figure 25 containing a portion of the raw B-scan with only the left object. Figure 27(b) shows the same section after application of the Vertical Offset Filter (VOF) with the object superimposed upon the filtered scan, and (c) without the object superimposed. The noticeable artefacts in this image are the hyperbolas located at the top and bottom of the object, and the reflections from the right hand object that appear in the latter time of the image (12 ns at approximately 0 m scan axis to about 8 ns at approximately 0.5 m scan axis).

After the operation of the VOF algorithm, the image in Figure 27(c), was obtained. As can be seen, the hyperbola structures were removed, and the image consists essentially of the top and bottom of the objects. The extra reflections from the right hand object have almost entirely been removed.
3.4. IMPROVING TIME DOMAIN IMAGES

3.4.2 Real Results

The synthetic experiments were reproduced using a 2 GHz SiropulseII GPR system from CSIRO (Aust). The test environment as illustrated in Figure 28 was assembled by placing the sample on a 3 mm aluminium plate, with the antenna suspended from a timber rail directly above the sample. The antenna was then run along the rail, recording a B-scan over the sample.

In the first set of experiments, the sample was a piece of machined solid wood of dimensions 0.17 m x 0.17 m x 0.10 m (LxDxW) supported on a dowel base to a height of 0.49 m above the metal plate. Figure 29 shows the raw data obtained from the GPR system. The image shows a dominant reflection from the metal plate and antenna ringing in the early time interval. There was also some dipping features in the traces between 0-0.5 m and 1.2-2.0 m caused by the supports of the antenna rail. The wood block is not immediately obvious in the unfiltered image, however the top can be seen at about 2.5 ns.

Three scans were recorded, with the antenna lifted vertically 100 mm between scans, thus creating an offset in the vertical direction. Before the VOF could be applied to the data
set, the three scans needed to be aligned. The three data sets were manually aligned by identifying the midpoint between the first arrival of the leading edge of the sample, and the last arrival of the trailing edge of the sample. The data sets were trimmed of traces to a common length, and zero-padding was applied to the offset data to ensure the scans had a common depth. The resulting data sets were three B-scans of the same depth and width, with data vertically offset by an amount equal to the vertical lift of the antenna.

After filtering the images with the VOF, Figure 30 was obtained. The aluminium sheeting on the floor was immediately apparent at about 5 ns. The top of the wood block was visible at about 1.5 ns which corresponded to the shifted raw data. The top of the block was recorded across 158 samples. Based on the horizontal spacing of 1.15 mm/trace, the top of the wood block was calculated to be 0.18m, closely matching the actual dimensions. The bottom of the wood block is apparent at about 3 ns. The image also presents the dipping floor under the object representing the reduced velocity of the signal through the higher relative permittivity of the wood block.

Further experiments were conducted on complex samples of rock fragments. Rock samples were obtained and manually sifted to uniform fragment sizes of <25 mm, 25-50 mm and 50-100 mm. These were randomly placed in separate plastic boxes of dimensions 0.5 m x 0.2 m x 0.4 m (LxDxW) and placed on an aluminium plate (see Figure 31). Figure 32
3.4. IMPROVING TIME DOMAIN IMAGES

Figure 30: Real GPR scan over wood - VOF filter applied.

shows the raw data from the GPR unit. In this image it can be seen that the floor presented, as in the previous experiment with the wood block, as a continuous and solid reflection generally at a constant time. The rock fragments are observed as a turbulent area in the centre of the image.

Faint artefacts are present from about 2 ns until the concrete floor in early and late traces which were reflections from the supporting structure for the antenna. There were also considerable reflections appearing below the floor, however these were multipath/late arrival reflections from the sides of the structure and the beam supporting the antenna. These artefacts are considered unwanted reflections cluttering the image.

Once again the images were manually aligned, in a similar method to that above, before the VOF was applied to the combined data. The images were aligned using the floor as a common vertical component to determine the actual vertical offset. The horizontal alignment used the leading edge of the container as a common feature in the three B-scans.

After application of the VOF over the images, Figure 33 was obtained, which showed the surface profile of the rock fragments, the aluminium sheet beneath the sample, and significant reflections beneath the surface. The floor is shown at about 6 ns due to the effect of the change in velocity of the signal by the increased permittivity of the rocks. The side reflections and multipath/late arrival reflections were all removed. The image was
Figure 31: Experimental setup to capture VOF data over rock samples.
3.4. IMPROVING TIME DOMAIN IMAGES

Figure 32: B-Scan over plastic container of rock fragments 25mm to 50mm - raw data.

augmented to assist interpretation by tracing the significant reflections from the surface of the rocks, within the container.

The footprint of the antenna beam was approximately 1m in the \(x\) and \(y\) directions at the elevations used. The surface profile depicted in the images corresponded with the surface profile of the rock fragments providing a much finer resolution than the footprint would suggest possible.

3.4.3 Imaging Discussion

It has been shown in Figure 27 that the VOF improves the resolution of the simulated data, removing clutter from the original. The operation is also very fast over each A-scan data set, and allows construction of B-scans from the filtered data. The algorithm has also been implemented on real GPR data (Figures 30 and 33) and showed similar clutter removal in the filtered B-scans. Further experiments are required to determine the resolution of the data filtered using VOF.

There is an additional cost associated with using the VOF algorithm in the acquisition of the data set. The VOF requires at least 2 identical A-scans with a vertical shift occurring between the two scans. This additional acquisition time may be a problem in certain
applications. In the particular application under study (see Chapter 1) this additional cost could be reduced by using a horizontal array of antennas and the motion of the image acquisition vehicle. As the vehicle approaches the draw point, the antennas will be offset in relation to the draw point - equivalent to the vertical offset in Figure 28. Each set of traces can then be processed individually, with an adjustment for the offset distance. The processed trace data could then be compiled to create a B-scan for further image analysis.

The real data sets presented in this paper were manually aligned before applying the VOF algorithm. In the application presented above, data would normally be collected as A-scans. The vertical alignment offset can be easily calculated from either the first arrival reflection, or using additional sensors, such as a laser sensor. As long as the vehicle is approaching perpendicular to the sample, the data is likely to be horizontally aligned. In other applications, the set-up and acquisition of A-scans would need to consider the alignment in the vertical and horizontal planes.

Further analysis of the data is required to demonstrate the resolution achievable under operation of the filter, and the correspondence of interior reflections to objects within the target structure. Further work is also proposed in automating the algorithm to determine the offset in complex environments.
3.5 Conclusion

This Chapter introduced the radar system used for the current project. The operating characteristics were established through experiments, including preliminary tests in the ore from the mine. Rock pile imaging was one method identified in Chapter 2 as a possible solution to the research questions posed in the Introduction. Images were captured through small rock piles in plastic crates which demonstrated the underlying premise that reflections will not originate in solid rock, providing a means of identifying such large fragments.

The problem of lateral reflections cluttering the image was partially solved using a new algorithm developed for this research. The Vertical Offset Filter (VOF) provides a new method to remove lateral reflections using the physical motion of the antenna. This method promises to have application beyond the current research project.

As stated in the preamble of this Chapter, the main purpose of this study is to design a system capable of assisting an underground mining operation as described in Chapter 1, and the results would be assessed in this context. While the rock imaging outlined, together with the new method of filtering lateral reflections, has been demonstrated to provide a potential solution to the research questions, a number of practical problems remain with this method.

Firstly, the time to acquire images would be too long for the mine production cycle. In order to obtain a 2D scan through the rock pile, a scanning mechanism would be required on the acquisition vehicle. The antenna would be required to scan across about 4 m with enough time for the vehicle to enter and exit the drawpoint between LHD access times.

Ideally the antenna would be mounted on the LHD and acquire images during and after collection of a load. This was deemed unsuitable and, indeed, impossible due to the extreme rugged environment and the delicate nature of the antennas. Any antenna structure on the LHD would simply be destroyed in normal production use. Also, the only suitable mounting place for the antenna which provided some view of the rock pile was immediately beneath the steel bucket at the front of the LHD. This large, conductive reflector would likely obscure any signal returns from the rocks.

A secondary acquisition vehicle would have to be very nimble to enter the drawpoint, scan the rock face, and exit before the LHD returned. The scanning mechanism required to acquire images across the entire width of the drawpoint would likely exclude ‘nimble’ being an appropriate adjective of an autonomous vehicle in an underground mine scenario.
For these reasons the work on the Vertical Offset Filter was stopped and alternative solutions to the problem were investigated. One of these was the use of volumetric analysis of the rock pile. This method would simplify data acquisition and not require any additional vehicles. This approach is presented in the next chapter.
Chapter 4

Volumetric Analysis of Rock Piles

A major problem identified in the previous chapter is the data acquisition platform for the GPR system. The previous chapter looked at GPR images in the time domain to identify large rocks which, unlike images from a digital camera, are not clear and require a lot of interpretation to identify objects. One reason for this lack of clarity is the influence of clutter in the signal caused by the broad beam radar signal.

A new filtering technique was shown which reduces this clutter, Using the physical movement of the antennas can assist in improving GPR images, however a dedicated rail to move a single antenna was likely to be too susceptible to damage and difficult to manoeuvre through tunnels. Mounting the antennas on a vehicle provides a potential solution, allowing an array of antennas to utilise the approach of the vehicle for filtering. In this case, however, an LHD vehicle mounting would not provide a suitable field of view for the antennas as previously discussed. The challenging environment of an underground mine requires a robust and maintainable platform for image acquisition.

A fixed antenna system offers the ability to be within a protective container away from vehicle collision and can be utilised to take continuous measurements to improve detection rates for any larger boulders. Such a system though would likely employ a small number of antennas, and would not be able to benefit from movement filtering as outlined in Chapter 3. Hence, a different method of detection is required.

A fixed antenna system will interrogate the same space, within which there is a constant volume. This type of system will not achieve high resolution images of the rock components. Instead, the radar response to the material within that volume will allow interpretation of the entire volume, and give an opportunity to infer the contents of that space.
In the case of the underground mine drawpoint presented in Chapter 1, the aim is to determine if an oversized fragment is present. With the antennas fixed on either side of the drawpoint, the amount of rock present could be estimated by measuring the bulk density of the material within the volume. The bulk density measurement would allow an inference as to the presence of a large fragment.

This chapter presents research in measuring material characteristics of the whole volume, rather than individual components within the mixture. Material characteristics, including experimental set-up and sample selection, will be discussed in Section 4.1. The relationship between sample bulk density and the radar response as a method of determining the presence of a large rock will be explored in Sections 4.2 and 4.3.

This research has been published in [70] and [79].

4.1 Experimental Design

The GPR system used was a SiroPulseII system developed by CSIRO (Australia) and documented in Section 3.2. The antennas used in the research presented in this chapter are separate 1.4 GHz antennas, allowing transmit and receive antennas to be placed in different physical arrangements. The antennas were arranged in a trans-illumination set-up, as shown in Figure 34.
As previously described, approximately 20 t of ore samples were obtained from the mine which was manually sifted to provide samples of uniform rock fragment sizes and enabled the removal of contaminants. The rock samples were placed in plastic crates and have been categorised as Low Density, Medium Density or High Density samples, as described below.

The crated ore samples were placed between the antennas with minimal separation between the crates and antennas, as depicted in Figure 34. With this arrangement the signal propagates through the media once and will not be reflected back to the receive antenna as was the case with reflective imaging in the previous chapter. This method of capture will therefore assist in reducing attenuation and improving the depth of penetration.

The signal was recorded for a minimum of 5 seconds, resulting in approximately 2000 individual A-scans being stored for each sample. The signal propagation path is the distance between the antennas placed on opposite sides of the crates, as depicted in Figure 34 and shown in Table 4.

The acquired scan was then pre-processed as outlined in Section 2.3.1, using `csuSignal.m` code listed in Appendix A, by:

- discarding the first and last 25% of A-scans
- obtaining the average A-scan over the remaining traces
- removing DC
- de-wowing the signal.
- normalising the signal to a nominal value

Further investigation of signal properties was carried out, as described below.

### 4.1.1 Rock Samples

The ore supplied was hand sifted and sorted by sieving with sizes ranging from a 100 mm down to a 5 mm sieve resulting in sorted fragments sizes as listed in Table 4. All visible contaminants were removed (concrete, fibre reinforcing, metal etc.) to ensure uniform material.

The distance between the antennas $Tx$ and $Rx$ is shown in column 2 of Table 4. The antennas were placed as depicted in Figure 34 and were offset from the sides of the crate.
Figure 35: Low density rock samples. The right crate is a mixture of foam and ore fines. The left crate contains only foam.

by approximately 8 mm. The signal path between the antennas was through the longest dimension of the crate, parallel to the ground.

The crates containing the rock samples were weighed, internal dimensions measured and bulk density calculated using

\[
\rho = \frac{M}{V} \text{g cm}^{-3}
\]  

where \( \rho \) is the bulk density of the material, \( M \) is the mass, and \( V \) is the volume. The bulk density of the samples as listed in Table 4 were broadly categorised according to the bulk density as low, medium or high density samples.

**Low Density**  Low density samples were those with a bulk density of less than 1.0 \( g/cm^3 \) (see column 3 of Table 4). These four samples included the benchmark experiment of recording the signal through air. Additional low density samples were created by using common foam packaging ‘peanuts’ as a filler together with rock particles (Figure 35). A test was conducted on a crate filled with foam. Foam was mixed with the fine 0 mm to 5 mm rock material to create a low density sample. The bulk density of this sample was 0.625 \( g/cm^3 \).

**Medium Density**  The 12 samples in the medium density category were all samples created using uniform fragment sizes. The fragments were sifted to a common fragment size of 0-5 mm, 5-12 mm, 12-25 mm, 25-50 mm and 50-100 mm. The bulk density of
Table 4: Characteristics of manually sifted rock samples from the underground mine

<table>
<thead>
<tr>
<th>Sample</th>
<th>Distance (mm)</th>
<th>Bulk Density (g/cm³)</th>
<th>Velocity (mm/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low Density</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>747</td>
<td>≈ 0</td>
<td>299.8</td>
</tr>
<tr>
<td>Empty Crate</td>
<td>410</td>
<td>≈ 0</td>
<td>301.9</td>
</tr>
<tr>
<td>Crate w. Foam</td>
<td>410</td>
<td>0.005</td>
<td>295.5</td>
</tr>
<tr>
<td>Foam + 0-5mm</td>
<td>410</td>
<td>0.625</td>
<td>264.5</td>
</tr>
<tr>
<td><strong>Medium Density</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5mm</td>
<td>540</td>
<td>1.540</td>
<td>157.0</td>
</tr>
<tr>
<td>0-5mm</td>
<td>540</td>
<td>1.528</td>
<td>152.9</td>
</tr>
<tr>
<td>0-5mm</td>
<td>540</td>
<td>1.638</td>
<td>149.0</td>
</tr>
<tr>
<td>0-5mm</td>
<td>540</td>
<td>1.609</td>
<td>150.9</td>
</tr>
<tr>
<td>5-12mm</td>
<td>590</td>
<td>1.448</td>
<td>160.7</td>
</tr>
<tr>
<td>5-12mm</td>
<td>590</td>
<td>1.496</td>
<td>158.0</td>
</tr>
<tr>
<td>12-25mm</td>
<td>590</td>
<td>1.432</td>
<td>158.7</td>
</tr>
<tr>
<td>25-50mm</td>
<td>590</td>
<td>1.436</td>
<td>155.4</td>
</tr>
<tr>
<td>25-50mm</td>
<td>590</td>
<td>1.474</td>
<td>153.5</td>
</tr>
<tr>
<td>25-50mm</td>
<td>590</td>
<td>1.512</td>
<td>154.8</td>
</tr>
<tr>
<td>50-100mm</td>
<td>590</td>
<td>1.270</td>
<td>160.0</td>
</tr>
<tr>
<td>50-100mm</td>
<td>590</td>
<td>1.262</td>
<td>162.1</td>
</tr>
<tr>
<td><strong>High Density</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock + 0-5mm</td>
<td>420</td>
<td>1.692</td>
<td>139.6</td>
</tr>
<tr>
<td>Rock + 0-5mm</td>
<td>420</td>
<td>1.694</td>
<td>128.6</td>
</tr>
<tr>
<td>Rock + 0-5mm</td>
<td>420</td>
<td>1.849</td>
<td>143.2</td>
</tr>
<tr>
<td>Rock + 0-5mm</td>
<td>420</td>
<td>1.900</td>
<td>110.7</td>
</tr>
<tr>
<td>Rock + 0-5mm</td>
<td>420</td>
<td>1.966</td>
<td>107.7</td>
</tr>
<tr>
<td>Solid</td>
<td>600</td>
<td>2.740</td>
<td>96.2</td>
</tr>
</tbody>
</table>
these samples ranged from $1.262 \text{ g/cm}^3$ to $1.638 \text{ g/cm}^3$. Figure 36 shows two examples of this material.

The height of the samples in the crates were kept as near to the top of the crates as possible, however the coarser rock samples presented a more variable surface than the smaller fragment sizes. The boxes were, at times, stacked for storage, and this resulted in some compaction of the material. This compaction provided a number of samples of similar fragment sizes, at different bulk densities (see Table 4).

**High Density** A large rock fragment of approximate dimensions 600 mm x 600 mm x 300 mm was used to establish the characteristics for the solid material. The bulk density of the solid rock was determined from measurements on a number of smaller samples, and confirmed from external studies on the geological materials at the site [108]. The solid rock had a very irregular surface making antenna coupling difficult.

A number of high density samples were constructed using smaller rock fragments (approximately 250 mm diameter) and pulverised material. These rock fragments were placed in the same plastic crates as the low and medium density samples, and surrounded by 0-5 mm fines to create a similar signal path and coupling as the other crated samples. Figure 37 shows one of the high density samples, with the rock fragment highlighted with yellow paint. This provided some high density samples approaching the bulk density of the solid rock fragment, with a smooth surface for optimal antenna coupling.
4.1. EXPERIMENTAL DESIGN

Figure 37: High density rock samples contained a single, large fragment embedded in fines. The large rock in the photograph has been exposed for the picture.

4.1.2 Electrical Characteristics of the Ore

The relative permittivity of the solid ore was determined through reflection coefficients on sifted material (0-5 mm in Table 4) as described in Section 2.4:

\[ \epsilon_r = \left( \frac{A_p + A_0}{A_p - A_0} \right)^2 \] (43)

where \( A_p \) is the amplitude of reflection from a metal sheet and \( A_0 \) is the amplitude of the reflection from the material. The fine samples (0-5 mm) produced a smooth interface for recording the reflection coefficients. The relative permittivity \( \epsilon_r \) of the fine material (\( \rho = 1.86 \text{g/cm}^3 \)) was measured at 5.44. Mixture models presented in Section 2.4.1 included the CRIM model (equation (30)) and LLL model (equation (31)) which are standard volumetric models based on the fractional volume and permittivity of the components. These equations allow the determination of characteristics of a solid from a mixture. In measuring a characteristic of the mixture, and knowing the fractional parts of the mixture, the character of the solid can be determined.

The samples under investigation contained only two components, rock and air. The air has known permittivity (\( \epsilon_r = 1 \)). By measuring the permittivity of the mixture, the permittivity of the solid \( \epsilon_s \) can be estimated using the CRIM model and the LLL model from Section 2.4.1 which are reproduced as follows:
\[ \varepsilon_s = \left( \frac{\sqrt{\varepsilon_m + V_m} - 1}{V_m} \right)^2 \]  \hspace{1cm} \text{(44)}

\[ \varepsilon_s = \left( \frac{3\sqrt{\varepsilon_m + V_m} - 1}{V_m} \right)^3 \]  \hspace{1cm} \text{(45)}

where \( \varepsilon_m \) is the complex permittivity of the mixture, \( V_m = \rho_m / \rho_s \) is the fractional volume of the solid material in the mixture derived from the known density of both the solid (\( \rho_s \)) and the mixture (\( \rho_m \)). Applying these equations to the previously measured data, the solid material had a relative permittivity \( \varepsilon_s \approx 8.8 \) according to the CRIM equation (44) and \( \varepsilon_s \approx 9.5 \) by the LLL equation (45).

The calculations confirm the value of \( \varepsilon_r \approx 9.7 \) estimated in Section 3.2.2 using velocity calculations. This also confirms that the LLL equation is an appropriate mixture model for the problem under consideration. This value, and the LLL equation, will be adopted for the permittivity calculations outlined below.

A geophysical study of the ore zone found that the apparent resistivity of the ore zone to be < 300 \( \Omega \) m [108]. Conductivity is the reciprocal of resistivity such that the maximum conductivity \( \sigma = 0.003 \text{ S m}^{-1} \). At the GPR operating frequency (1.4 GHz) and permittivity as estimated above, the loss factor \( \tan\delta \) was evaluated

\[ \tan\delta = \frac{\sigma}{\omega \varepsilon_r} = \frac{0.003}{(2 \times \pi \times 1.4 \times 10^9)(9.7)(8.85 \times 10^{-12})} = 0.004 \]

Since \( \tan\delta \ll 1 \) the velocity of signal propagation was estimated using equation (19). The relative permittivity of the solid rock was estimated from velocity measurements through a large, solid fragment (see Table 4) to be approximately 9.7 according to equation (48), which agreed with the estimate obtained by equations (43) and (45).

### 4.2 Velocity and Bulk Density

Mixture models allow the determination of solid material characteristics using measurements on particulate material, as described in Section 2.4.1. This was also demonstrated in the previous Section to confirm the relative permittivity measurements of the solid through measurement of the fines. For a two-phase air-solid mixture, equation (45) predicts the relative permittivity of the solid component, \( \varepsilon_s \), where \( \varepsilon_m \) is the complex permittivity of
4.2. VELOCITY AND BULK DENSITY

the mixture and $V_m$ is the volume fraction of the solid material such that $V_m = \rho_m / \rho_s$.

To determine the relative permittivity of a mixed sample ($\epsilon_m$), given the relative permittivity ($\epsilon_s$) and bulk density ($\rho_s$) of the solid material, and bulk density of the sample ($\rho_m$) equation (45) can be rearranged as:

$$\sqrt[3]{\epsilon_m} = \frac{\sqrt[3]{\epsilon_s} - 1}{\rho_s} \rho_m + 1$$ (46)

The large volumes of fragmented ore must be sampled quickly due to the cycle times for the LHD. The velocity of propagation of the radar signal through the material is influenced by both the permittivity and dielectric losses caused by conductivity.

As outlined in Section 4.1.2, when the propagating media is a low-loss material, such that $\tan\delta \ll 1$, the velocity equation (16) simplifies down to

$$v_r = \frac{c}{\sqrt{\epsilon_r}}$$ (47)

where $v_r$ is the propagation velocity, $c$ is the speed of light ($3 \times 10^8$ m/s) and $\epsilon_r$ is the relative permittivity of the medium. Through a simple rearrangement of equation (47), the propagation velocity can therefore be used in equation (48) to estimate the relative permittivity of the material.

$$\epsilon_r = \left(\frac{c}{v_r}\right)^2$$ (48)

From the relative permittivity the bulk density of the mixture can be estimated as shown in equation (49) derived from equation (46).

$$\rho_m = \frac{\sqrt[3]{\epsilon_m} - 1}{\sqrt[3]{\epsilon_s} - 1} \rho_s$$ (49)

As there are only two components in the mixture, the quantity of rock in the sample can be determined from the bulk density and, as the bulk density approaches that of the solid rock, the presence or absence of a large fragment in the current sample can be inferred.
4.2.1 Time Zero Calibration

Calculating the velocity of the signal across a known distance requires accurate timing of the arrival time relative to the transmit time. As outlined in Section 2.2.3, time zero drift is one of the leading causes of errors in GPR data collection. In a typical bi-static antenna configuration, the receive antenna is located close to the transmit antenna, permitting the recording of the direct air wave in the signal. Given the proximity of the receive antenna to the transmit antenna, this gives a simple method of determining time zero in the receive signal. Manufacturers recommend a typical ‘warm-up’ period of approximately 10 minutes to allow the electronics to stabilise, reducing the effect of the drift in time zero. For a remote antenna such as is used in this research or in other Common Mid Point (CMP) GPR surveys, tracking the position of time zero is more difficult.

To determine the extent of drift in time zero for the antenna system used in this research, the transmit-receive antennas were separated by an air gap of 1000 mm, and a reading taken every 5 minutes for 2 hours. Over this time, the peak drifted from sample 265/512 to sample 235/512, representing a drift of nearly 0.5 ns which corresponds to about 150 mm in air (see Figure 38).

Time zero drift can be compensated by using a time factor [68], however a better method...
4.2. VELOCITY AND BULK DENSITY

is proposed that transforms the absolute measurement of the arrival peak into a relative measurement, thereby removing the need for accurate time keeping and recalibration of the drift compensation.

Arranging the antennas such that there is a receive antenna \((R_x_1)\) in close proximity to the transmit antenna \((T_x)\), as well as the opposite receive antenna \((R_x_2)\), as shown in Figure 34, allows the time zero point to be determined from the near receive antenna \((R_x_1)\), and the offset applied to the remote antenna \((R_x_2)\). In this way the remote antenna remains in synchronisation with the transmit antenna, and an accurate time distance can be measured between the two antennas. This arrangement has been tested and the range to the remote receive antenna \((R_x_2)\) was found to be repeatable over a long time period showing no noticeable drift when measured relative to the antenna \((R_x_1)\) in proximity to the transmit antenna.

Two methods were tested to establish time zero:

- the zero crossing before the first peak of the direct wave, and
- the peak of the positive signal envelope from the Hilbert Transform of the time signal.

and

Figure 39 shows the direct wave as received by the adjacent receive antenna \((R_x_1)\) (red), and the received signal at the opposing antenna \((R_x_2)\) (blue). The relative difference was measured as the time between the early arrival on the direct wave, or red signal, and the later arrival of the signal on the opposing antenna (blue). Over a test distance measured at 747 mm, the relative time of signal arrival at both receive antennas consistently measured 746 mm between the transmit and remote receive antenna. While this method proved accurate (less than 0.1% error), determining the zero crossing was very difficult in the presence of signal noise.

A second, more robust, method was found by using the Hilbert Transform of the time signal. The Hilbert Transform allows a complex time signal to be constructed from a real-valued input signal, the imaginary part being the original real signal with a 90\(^\circ\) phase shift \([113]\). The envelope of the original real signal can be more accurately extracted using the discrete Hilbert Transform, which allows the peak of the envelope to be easily detected \([114]\).

Figure 40 shows the Hilbert Transform of both signals as the positive signal envelope overlain in time. The peak of each envelope represents an accurate relative time of arrival
for each signal. The relative difference was measured as the time between the early arrival on the direct wave at antenna $Rx_1$ and the later arrival of the signal at antenna $Rx_2$ (see Figure 34).

When the signal is emitted from antenna $Tx$ the energy begins travelling toward both receive antennas. Its arrival at $Rx_1$ is the direct wave as previously described. Figure 41 shows that when the signal arrives at $Rx_1$, the signal has also travelled an equivalent distance toward antenna $Rx_2$ identified as the point marked 'A'.

The time measured between the signal arrival at 'A' and antenna $Rx_2$ is the relative time difference between the signal arriving at both receive antennas. When the signal arrives at $Rx_2$ the total travel time from the source $Tx$ is the relative time between $Rx_1$ and $Rx_2$ plus the calculated time the signal would take from $Tx$ to $Rx_1$.

To calibrate this time against the distance between the antennas the measured offset between $Tx$ and $Rx_1$ was needed. The distance, $d$, between the two receive antennas, $Rx_1$ and $Rx_2$, is

$$d = c(t_2 + t_1)$$

(50)
4.2. VELOCITY AND BULK DENSITY

Figure 40: The Hilbert Transform of the time domain signal allows easy identification of the pulse arrival. The relative time between pulses enables calculation of the signal propagation time through the material.

Figure 41: Using the relative arrival times of the signal at offset antenna $Rx_1$ and remote antenna $Rx_2$ to calibrate the distance measured between the antennas.
where \( c \) is the speed of light, \( t_1 \) is the calculated time for the direct wave to arrive at antenna \( Rx_1 \) and \( t_2 \) is the relative time for the signal to arrive at antenna \( Rx_2 \) (distance 'A' to \( Rx_2 \) in Figure 41).

Over a test distance of 1000 mm, readings were taken to test this method of identifying the signal arrival time. The average relative time of signal arrival between \( Rx_1 \) and \( Rx_2 \) was 3.223 ns and the offset distance between antennas \( Tx \) and \( Rx_1 \) is 30 mm which would take 0.1 ns for the direct wave to traverse. The average arrival time at antenna \( Rx_2 \) for the signal propagation is 3.323 ns. Using equation (50) the calculated distance was 996.2 mm, an error of 0.4%.

The result of experiments to identify the best candidate position for establishing time zero indicated that using a Hilbert Transform of the signals to determine the peak in the time domain was accurate, fast and repeatable for use in automated scripts.

**4.2.2 Velocity Analysis Results**

Once the time zero point was calibrated and repeatable for velocity measurements, data was recorded through each of the rock crate samples. Each measurement recorded a minimum of 500 scans through the sample which were then averaged to a single scan. All measurements were repeatable and showed no change over the course of the experiments.

The samples through air and solid rock were used as calibration points. These points effectively established the lower and upper boundaries respectively. The velocity of the signal in air matched that of the speed of light at approximately 299.79 mm/ns.

The sifted rock samples were all defined by their densities as belonging to the 'Medium Density' class. In order to provide samples in the upper and lower density ranges, samples were created using a mixture of materials. Samples with a 'Low density' were created with foam packing noodles as previously described. Signal velocities recorded through the foam noodles only within the crate showed there was no discernible effect from the foam noodles on signal velocity (see Table 4).

The low density ore sample exhibited a higher signal velocity than the medium density ore samples, which in turn exhibited higher velocities than the high density samples. The results, plotted in Figure 42, show that the relationship between the calculated cube root of the relative permittivity and the bulk density of the sample is approximately linear. As sample bulk density increases towards that of solid ore the relative permittivity also increases, causing the signal velocity to decrease.
4.2. VELOCITY AND BULK DENSITY

Figure 42: Graph of experimental results showing the relationship between the cubed root of the relative permittivity to bulk density of a sample.

The linear regression through the data ($R^2 = 0.981$) gives rise to equation (51)

$$\sqrt[3]{\epsilon_m} = 0.398\rho_m + 1$$  \hspace{1cm} (51)

The relationship (equation 51) has been forced through the point (0,1) to reflect the permittivity $\epsilon_r\epsilon_0 = \epsilon_0$ of free space. When the sample density $\rho = 0$, the relative permittivity of the sample is expected to be $\sqrt[3]{\epsilon_r} = 1$. Data has also been recorded very close to this point which indicates the value of the intercept is 1.0 [115].

By recording the time the signal takes to propagate over the distance between the antennas, the signal velocity can be estimated, and thus, the bulk density calculated according to equation (49). As the calculated bulk density $\rho_m$ approaches that of solid rock ($\rho_s$) the ratio of rock to air in the signal path increases. If the ratio of rock to air in the signal path were to exceed a threshold value, this would correspond to the presence of over-sized fragments.

This provides a solution to the proposed research question. The relationship between bulk density and relative permittivity could thus provide a method of determining the presence of large fragments at the drawpoint.

The bulk density of the sample under illumination compared to the bulk density of solid rock allows a ratio of rock to air to be calculated for the sample. These results are from
laboratory experiments and construction of a full-scale test system is currently being investigated in a separate project. This will permit the study of rock flows and enable the determination of the threshold values when a large rock may be present in a drawpoint.

The current antennas operate at 1.4 GHz and the results obtained have demonstrated this frequency is effective over the experimental sample distances of 1.1 m. Over the typical width of a drawpoint (5 m), a lower frequency will be necessary to penetrate the rock with sufficient signal power for detection. The full-scale system being constructed will also allow investigation of suitable operating frequencies and antenna placement.

The ore extracted from the drawpoint is a constant flow of material from the ore body through the drawpoint. At no time is there expected to be a clear drawpoint enabling calibration of the signal start time between opposing transmit and receive antennas. A method of calibrating the start time by using a multi-channel system with adjacent Tx-Rx antennas has been demonstrated and shown to provide a solution to the problem of drift over time.

4.3 Attenuation Experiments

As the GPR pulse propagates into the ore material, it suffers attenuation as a result of absorption, dispersion and scattering. The propagating wave is subject to three constitutive dielectric characteristics of the medium - complex dielectric permittivity ($\epsilon$), magnetic permeability ($\mu$) and electrical conductivity ($\sigma$). Magnetic permeability is negligible in non-ferrous minerals and can be ignored for the ore under consideration.

Attenuation can be measured in both the time domain and the frequency domain, as described in Section 2.4.1. As the signal propagates through the material, the amplitudes of the reflections in the time domain are attenuated. In the frequency domain, the higher frequencies are attenuated more than lower frequencies, presenting as a shift in the peak and/or centroid frequency of the received spectrum.

Experiments using reflection data on the same ore samples showed that there may be a relationship between the peak frequency downshift and the bulk density of the sample [79]. These experiments were conducted in reflection mode with a PEC beneath the sample, the results are not directly applicable to the research problem as it would be near impossible to replicate this in the mining environment. The results did however suggest that there may be a measurable frequency downshift effect from the rocks during attenuation of the signal.
The attenuation, \( \alpha \), of the GPR signal in many geological materials is approximated by a linear function of frequency by [83]:

\[ \alpha = \omega \left[ \frac{\mu \epsilon}{2} \left( \sqrt{1 + \tan^2 \delta} - 1 \right) \right]^{\frac{1}{2}} \]  (52)

where

\[ \tan \delta = \frac{\sigma}{\omega \epsilon} \]  (53)

and \( \omega = 2\pi f \) is the angular frequency; \( \mu = \) magnetic permeability, in Henries per meter; \( \epsilon = \) dielectric permittivity, in Farads per metre; \( \sigma = \) electrical conductivity, in Siemens per metre; \( f = \) frequency, in hertz. From equation (52) it can be seen that higher frequencies attenuate more than low frequencies [83].

Changes in bulk density will change the dielectric properties of the rock sample, \( \mu \), \( \epsilon \) and \( \sigma \), attenuating the transmitted radar signals. The spectrum centroid of the radar pulse experiences a downshift during propagation which can be attributed to dielectric losses as described in Section 2.4.1. This method of estimation needs the frequency data to be broadband making it easier to detect a change in the frequency distribution.

As demonstrated in the previous section, the cube root permittivity of the material as measured by the velocity of the signal has a linear relationship to the bulk density of the medium.

Using the same samples as in Section 4.1, and listed in Table 4, the attenuation was measured for the received signal. The antennas were set-up in the same manner, as shown in Figure 43 (previously shown as Figure 34).

### 4.3.1 Attenuation Results

The attenuation was measured using the 5 methods as described in Table 5 and in Section 2.4. The measurements for each metric are shown in Table 6 and discussed in the following paragraphs.

**Amplitude Attenuation – \( t_{Att} \)** The first measure, \( t_{Att} \), compares the maximum value in the time domain of the signal received at antenna \( Rx_1 \) to the signal received at antenna \( Rx_2 \) after travelling through the material. In the time domain, the peak values at the source
Figure 43: Schematic of dual channel antenna arrangement negating the need for calibration of zero time caused by drift.

<table>
<thead>
<tr>
<th>Method</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$t_{Att}$</td>
<td>attenuation of amplitude in the time domain (equation (21))</td>
</tr>
<tr>
<td>2</td>
<td>$e_{Att}$</td>
<td>attenuation of signal energy in the frequency domain (equation (23))</td>
</tr>
<tr>
<td>3</td>
<td>$Q_{peak}$</td>
<td>Q measurement using peak frequency downshift [102] (Bradford’s equation (29))</td>
</tr>
<tr>
<td>4</td>
<td>$Q_{cent}$</td>
<td>Q measurement using Bradford’s equation, but using the centroid frequency rather than peak frequency</td>
</tr>
<tr>
<td>5</td>
<td>$Q_{cfds}$</td>
<td>Q measurement using centroid frequency downshift [84] (equation (28))</td>
</tr>
</tbody>
</table>
### Table 6: Attenuation through crated rock samples sorted by sample bulk density

<table>
<thead>
<tr>
<th>Sample</th>
<th>Bulk Density $(g/cm^3)$</th>
<th>$\tau_{\text{Att}}$ (dB/m)</th>
<th>$\rho_{\text{Att}}$ (dB/m)</th>
<th>$Q_{\text{Peak}}$ (Q/m)</th>
<th>$Q_{\text{Cent}}$ (Q/m)</th>
<th>$Q_{\text{cdfs}}$ (Q/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$\approx 0$</td>
<td>19.63</td>
<td>24.70</td>
<td>-8.41</td>
<td>52.18</td>
<td>45.38</td>
</tr>
<tr>
<td>Empty Crate</td>
<td>$\approx 0$</td>
<td>21.33</td>
<td>21.08</td>
<td>43.73</td>
<td>64.07</td>
<td>27.65</td>
</tr>
<tr>
<td>Crate w. foam</td>
<td>0.005</td>
<td>19.38</td>
<td>24.92</td>
<td>46.44</td>
<td>53.81</td>
<td>46.78</td>
</tr>
<tr>
<td>Foam + 0-5mm</td>
<td>0.625</td>
<td>32.50</td>
<td>24.60</td>
<td>45.78</td>
<td>27.55</td>
<td>14.27</td>
</tr>
<tr>
<td>50-100 mm</td>
<td>1.262</td>
<td>44.06</td>
<td>36.66</td>
<td>20.17</td>
<td>17.79</td>
<td>8.94</td>
</tr>
<tr>
<td>50-100 mm</td>
<td>1.270</td>
<td>37.56</td>
<td>32.06</td>
<td>15.64</td>
<td>18.75</td>
<td>11.15</td>
</tr>
<tr>
<td>12-25 mm</td>
<td>1.432</td>
<td>14.85</td>
<td>14.01</td>
<td>-41.65</td>
<td>64.39</td>
<td>34.01</td>
</tr>
<tr>
<td>25-50 mm</td>
<td>1.436</td>
<td>23.82</td>
<td>21.09</td>
<td>15.44</td>
<td>37.39</td>
<td>15.29</td>
</tr>
<tr>
<td>5-12 mm</td>
<td>1.448</td>
<td>13.80</td>
<td>12.23</td>
<td>-91.66</td>
<td>63.05</td>
<td>32.85</td>
</tr>
<tr>
<td>25-50 mm</td>
<td>1.474</td>
<td>25.26</td>
<td>25.49</td>
<td>87.52</td>
<td>47.79</td>
<td>18.76</td>
</tr>
<tr>
<td>5-12 mm</td>
<td>1.496</td>
<td>12.96</td>
<td>12.37</td>
<td>17.93</td>
<td>54.60</td>
<td>34.06</td>
</tr>
<tr>
<td>25-50 mm</td>
<td>1.512</td>
<td>22.65</td>
<td>16.89</td>
<td>78.92</td>
<td>41.10</td>
<td>13.69</td>
</tr>
<tr>
<td>0-5 mm</td>
<td>1.528</td>
<td>10.47</td>
<td>9.53</td>
<td>34.99</td>
<td>46.47</td>
<td>25.41</td>
</tr>
<tr>
<td>0-5 mm</td>
<td>1.540</td>
<td>10.16</td>
<td>8.85</td>
<td>20.88</td>
<td>26.94</td>
<td>28.35</td>
</tr>
<tr>
<td>0-5 mm</td>
<td>1.609</td>
<td>11.05</td>
<td>10.83</td>
<td>22.44</td>
<td>29.83</td>
<td>31.64</td>
</tr>
<tr>
<td>0-5 mm</td>
<td>1.638</td>
<td>10.54</td>
<td>11.18</td>
<td>32.41</td>
<td>30.12</td>
<td>31.71</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.692</td>
<td>-0.63</td>
<td>3.35</td>
<td>80.81</td>
<td>59.64</td>
<td>37.27</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.694</td>
<td>17.89</td>
<td>19.85</td>
<td>17.41</td>
<td>45.95</td>
<td>36.57</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.849</td>
<td>20.91</td>
<td>22.28</td>
<td>-31.20</td>
<td>431.70</td>
<td>353.81</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.900</td>
<td>31.17</td>
<td>22.76</td>
<td>53.58</td>
<td>34.70</td>
<td>24.61</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.966</td>
<td>39.93</td>
<td>39.01</td>
<td>49.92</td>
<td>30.95</td>
<td>13.80</td>
</tr>
<tr>
<td>Solid</td>
<td>2.740</td>
<td>58.70</td>
<td>54.23</td>
<td>27.39</td>
<td>39.42</td>
<td>20.41</td>
</tr>
</tbody>
</table>
CHAPTER 4. VOLUMETRIC ANALYSIS OF ROCK PILES

In Table 6 there appears to be a relationship between the fragment sizes with smaller rocks (0-5 mm) having lower attenuation than the larger rocks (50-100 mm). Similarly, the samples with embedded rocks (Rock+Fin) increase, although one sample returned a negative result. Air samples, which would be expected to be quite low, were measured relatively highly and could be confused with the attenuation through rock samples.

Figure 44 shows the attenuation of amplitudes in the time domain for the material samples in Table 4. Overall, there appears to be a discontinuity in the attenuation measurements between 1.5 g/cm$^3$ and 2.0 g/cm$^3$, which is where we would expect most of the rock material to be located. Thus, there appears to be no clear relationship between attenuation and the bulk density of the samples.

**Energy Attenuation – $e_{Att}$** Amplitude attenuation only measures attenuation of the peak values rather than attenuation of the entire signal. After identifying the signal arrival time using the Hilbert Transform as described above, the wavelet for the source and received wave were extracted from the time domain signal as beginning 50 samples before the peak, and 100 samples after the peak.

A Fourier Transform of these wavelets was performed to obtain the signal spectrum of the
4.3. ATTENUATION EXPERIMENTS

source and receive wave [97]. In the frequency domain analysis performed in Section 3.1 it was noted that the effective spectrum through rock was 0–3 GHz. Frequencies above that cut-off had little or no energy.

The energy in each wavelet was then calculated according to equation

\[ E = \sum |X(f)|^2 \]  
(54)

where \( X(f) \) is the Fourier transform of the time domain signal \( x(t) \), and the attenuation of the signal is calculated by

\[ \text{Attenuation (dB)} = 10 \log \left( \frac{E_1}{E_2} \right) \]  
(55)

where \( E_1 \) and \( E_2 \) are the energy in the source and receive wavelets respectively.

Table 6 show the values for the signal energy attenuation through the samples. The results for signal attenuation appear very similar to the measured values for attenuation in the time domain. Figure 45 shows the attenuation in signal energy across the spectrum 0 GHz to 3 GHz. Similar to attenuation in the time domain (\( t_{Att} \)), there appears to be no relationship between the bulk density and the attenuation using \( e_{Att} \).
Q Measurement As discussed in Section 2.4.1, the Quality Factor describes the slope of the attenuation versus the frequency curve. Higher frequencies attenuate greater than lower frequencies, causing a downshift in the frequency spectrum. Hence, as the slope increases (lower Q values), attenuation increases.

For each of these wavelets, the Fourier Transform was taken over the wavelets identified using the peak in the Hilbert Transform as described earlier. The Q factor for each sample was then calculated using three related methods, as described in Section 2.4 and discussed below.

Centroid Frequency Downshift – \( Q_{cfd} \) The first method, \( Q_{cfd} \), Centroid Frequency Down Shift (CFDS) was first proposed as a seismic method of determining Q values and was applied to the GPR data. CFDS calculates the centroid frequency as the weighted average frequency using equations (26)–(28).

Figure 46 shows the Q values for samples previously described. Apart from one outlier, the Q value for all samples appeared to fall between 0-50 and there was no apparent relationship between bulk density and Q using the Centroid Frequency Downshift method.
4.3. ATTENUATION EXPERIMENTS

The second frequency measure, $Q_{\text{peak}}$, used the method described by [102]. The peak frequency is identified in each wavelet spectrum (both source and receive) and $Q$ calculated using equation (29).

Bradford’s measure of peak downshift occasionally returned negative Q values, as shown in Table 6, and visible in Figure 47. This occurred in a small number of cases where the peak frequency would appear to actually increase, possibly due to scattering, rather than decrease as expected.

The third method is a combination of the preceding two. The centroid frequency of the spectrum is calculated using equation (26) as the weighted average frequency. The downshift in the centroid peak is then measured between the source wavelet and the received wavelet.

As can be seen in Table 6 this method has not returned any negative values. A comparison between this method and the previous $Q_{\text{peak}}$ method shows that many results are similar, although this method has returned a large outlier for one value.

Figure 48 shows this method produces very similar results to the $Q_{\text{cfds}}$ method, and corrected the problem with negative Q-values from Bradford’s peak measure. Once again, however, there appeared to be no relationship between Q-values and bulk density.
Summary  The attenuation methods presented appeared to show that there was no relationship between the bulk density of the samples and the attenuation of the signal, despite previous indications [79]. A key difference between the methods presented above, and the method presented in [79] was the antenna arrangement, which previously used a reflection mode recording and a PEC beneath the samples to ensure a clear delineation between the rock sample and the concrete floor beneath. The results presented here used a trans-illumination antenna arrangement as described above.

The appearance of negative $Q_{peak}$ values in the Bradford method would indicate the signal has actually increased in energy between source and received wavelet. Obviously this is unlikely, suggesting another reason for the error in the calculation of Q. One possible reason for the error could be contamination of the signal that has travelled through the rock with signal energy that has escaped the confines of the sample container.

The experiments above used small crates to contain the sample. This likely led to a portion of the signal bleeding around the crate and travelling through the air to the receive antenna. This would contaminate the scan such that the received signal no longer contained only the energy travelling through the rock sample.

The small crates worked for the earlier velocity calculations as these are a point-to-point
4.4. ATTENUATION AND FRAGMENT SIZE

The attenuation of the samples in Table 6 was sorted according to the bulk density of the sample. By rearranging the samples by fragment size, as shown in Table 7, there does appear to be a relationship between the attenuation of the sample and the fragment sizes, particularly for those 0 - 100 mm fragments.

Amplitude attenuation in the time domain (tAtt) and frequency domain (eAtt) both appear to produce an approximately linear relationship between the attenuation of the signal and the approximate fragment size. Figure 49 shows the average attenuation for each fragment size between 0- 100 mm. For fragment sizes between 0-5 mm and 50-100 mm, the attenuation increases as the fragment size increases. The relationship for both metrics (tAtt and eAtt) are approximately linear, however the x-axis chosen is simply the mid-point of the fragment size range, so no logistic regression has been performed.

The increased attenuation from these samples is most likely due to the fragments sizes approaching the wavelength (λ) of the radar signal, causing increased scattering. When the ratio between the fragment size and the wavelength of the signal (at 1.4 GHz λ ≈
Table 7: Attenuation through crated rock samples sorted by fragment size

<table>
<thead>
<tr>
<th>Sample</th>
<th>Bulk Density ((g/cm^3))</th>
<th>(t_{Att}) (dB/m)</th>
<th>(e_{Att}) (dB/m)</th>
<th>(Q_{peak}) (Q/m)</th>
<th>(Q_{cent}) (Q/m)</th>
<th>(Q_{cdfs}) (Q/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0</td>
<td>19.63</td>
<td>24.70</td>
<td>-8.41</td>
<td>52.18</td>
<td>45.38</td>
</tr>
<tr>
<td>Empty Crate</td>
<td>0</td>
<td>21.33</td>
<td>21.08</td>
<td>43.73</td>
<td>64.07</td>
<td>27.65</td>
</tr>
<tr>
<td>Crate w. foam</td>
<td>0.005</td>
<td>19.38</td>
<td>24.92</td>
<td>46.44</td>
<td>53.81</td>
<td>46.78</td>
</tr>
<tr>
<td>Foam + 0-5mm</td>
<td>0.625</td>
<td>32.50</td>
<td>24.60</td>
<td>45.78</td>
<td>27.55</td>
<td>14.27</td>
</tr>
<tr>
<td>0-5 mm</td>
<td>1.528</td>
<td>10.47</td>
<td>9.53</td>
<td>34.99</td>
<td>46.47</td>
<td>25.41</td>
</tr>
<tr>
<td>0-5 mm</td>
<td>1.54</td>
<td>10.16</td>
<td>8.85</td>
<td>20.88</td>
<td>26.94</td>
<td>28.35</td>
</tr>
<tr>
<td>0-5 mm</td>
<td>1.609</td>
<td>11.05</td>
<td>10.83</td>
<td>22.44</td>
<td>29.83</td>
<td>31.64</td>
</tr>
<tr>
<td>0-5 mm</td>
<td>1.638</td>
<td>10.54</td>
<td>11.18</td>
<td>32.41</td>
<td>30.12</td>
<td>31.71</td>
</tr>
<tr>
<td>5-12 mm</td>
<td>1.448</td>
<td>13.80</td>
<td>12.23</td>
<td>-91.66</td>
<td>63.05</td>
<td>32.85</td>
</tr>
<tr>
<td>5-12 mm</td>
<td>1.496</td>
<td>12.96</td>
<td>12.37</td>
<td>17.93</td>
<td>54.60</td>
<td>34.06</td>
</tr>
<tr>
<td>12-25 mm</td>
<td>1.432</td>
<td>14.85</td>
<td>14.01</td>
<td>-41.65</td>
<td>64.39</td>
<td>34.01</td>
</tr>
<tr>
<td>25-50 mm</td>
<td>1.436</td>
<td>23.82</td>
<td>21.09</td>
<td>15.44</td>
<td>37.39</td>
<td>15.29</td>
</tr>
<tr>
<td>25-50 mm</td>
<td>1.474</td>
<td>25.26</td>
<td>25.49</td>
<td>87.52</td>
<td>47.79</td>
<td>18.76</td>
</tr>
<tr>
<td>25-50 mm</td>
<td>1.512</td>
<td>22.65</td>
<td>16.89</td>
<td>78.92</td>
<td>41.10</td>
<td>13.69</td>
</tr>
<tr>
<td>50-100 mm</td>
<td>1.262</td>
<td>44.06</td>
<td>36.66</td>
<td>20.17</td>
<td>17.79</td>
<td>8.94</td>
</tr>
<tr>
<td>50-100 mm</td>
<td>1.27</td>
<td>37.56</td>
<td>32.06</td>
<td>15.64</td>
<td>18.75</td>
<td>11.15</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.692</td>
<td>-0.63</td>
<td>3.35</td>
<td>80.81</td>
<td>59.64</td>
<td>37.27</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.694</td>
<td>17.89</td>
<td>19.85</td>
<td>17.41</td>
<td>45.95</td>
<td>36.57</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.849</td>
<td>20.91</td>
<td>22.28</td>
<td>-31.20</td>
<td>431.70</td>
<td>353.81</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.9</td>
<td>31.17</td>
<td>22.76</td>
<td>53.58</td>
<td>34.70</td>
<td>24.61</td>
</tr>
<tr>
<td>Rock+Fines</td>
<td>1.966</td>
<td>39.93</td>
<td>39.01</td>
<td>49.92</td>
<td>30.95</td>
<td>13.80</td>
</tr>
<tr>
<td>Solid</td>
<td>2.74</td>
<td>58.70</td>
<td>54.23</td>
<td>27.39</td>
<td>39.42</td>
<td>20.41</td>
</tr>
</tbody>
</table>
4.5. \textit{CONCLUSION}

0.21m) is less than 1, the scatterer can be considered a point scatterer and the signal will be scattered in all directions, leading to increased attenuation. However, when the ratio is greater than 1, as is the case for fragments larger than approximately 0.21 m, the incident signal will encounter a planar feature and the signal will undergo reflection or refraction and material loss.

In order to extract meaningful analysis, additional datasets containing rock fragments at different sieve diameters would be required. For the application presented in this thesis, however, the data is of limited value as the fragment sizes are too small to be of concern. The samples that include larger rocks (Rock+Fines and Solid) are of limited value as they are near to, or considerably larger than, the signal wavelength.

The data does, however, offer additional possibilities to remotely measure fragment sizes of crushed rock such as on a conveyor belt. The relationship between fragment size and attenuation suggests a radar system could monitor fragment sizes from the crusher before milling. Additional research would be required to analyse different fragment sizes, including mixed data, to determine the relationship between fragment size and scattering attenuation.

\section*{4.5 Conclusion}

This chapter has demonstrated a number of methods for calculating material characteristics using GPR as a volumetric measuring tool. A number of rock samples were created using small plastic crates and fragmented rock material. The fragmented rock material ranged from 0-5 mm fines, through various sifted rubble sizes, and included some solid fragments. Additional inclusions to the samples were air and foam packaging noodles.

The samples had bulk densities of 0 (air), low ($\rho < 1.0g/cm^3$), medium ($1.00 < \rho < 1.65g/cm^3$) and high ($1.65 < \rho < \text{solid}$).

Results were shown that established a relationship between the bulk density and the signal velocity through the sample. From the velocity the permittivity of the sample was estimated. A linear relationship between the bulk density and the square root of the permittivity was established.
A linear relationship between the bulk density and frequency downshift had been reported in an earlier publication using reflection mode scans. With the antennas in a trans-illumination set-up, there appeared to be no relationship between the attenuation measured in the time domain and the frequency domain to the bulk density of the samples.

It was noted that one of the methods produced nonsensical negative Q-values, which would suggest signal energy increasing. It is proposed that the signal was bleeding around the small crates, contaminating the results of the attenuation experiments. These problems would likely be corrected with a larger container, allowing also for larger fragment sizes.

Additional research was identified in the relationship between fragment size and scattering attenuation. This offers further applications in measuring fragment sizes remotely post-crusher.
Chapter 5

Large Rock Detection

The previous chapter demonstrated a relationship between the electrical characteristics of the rock sample, as measured by the velocity of the GPR signal, and the bulk density of the sample. The velocity of the signal through the ore sample was used to measure permittivity of the sample and a relationship between the bulk density and the cube root of permittivity was shown. These results suggested that the amount of rock present in the sample alters the signal, such that the presence of an oversized fragment can be inferred.

Velocity analysis on its own is, however, unlikely to be sufficient to determine whether a large rock is present. Velocity analysis estimates the average permittivity through the rock pile. In the event that both a large rock and a large void was present in a scan, the bulk density measurement would indicate a much lower value than solid rock. This could be interpreted to indicate no large rock was present. Additional methods are therefore required in combination with the velocity measurements.

The attenuation results were inconsistent because the small sample crates allowed the signal to bleed around the outside of the crate and contaminate the signal propagating through the ore. Due to the broad beam width of the radar, the signal escaped the confines of the crate and proceeded through air to the receive antenna. A bigger sample container was required to minimise this bleeding and ensure the propagating signal remained within the ore body.

This chapter begins with a description of just such a container – a large wooden box constructed to allow larger sample volumes and the use of larger rock fragments. Section 5.1 continues to describe the rock samples and some preliminary characteristics of the box itself. Sections 5.2 and 5.3 describe results over the base conditions of an empty box.
and the background rubble. Section 5.4 looks at a small training data set that includes all the types of rock under analysis. From this training set, a logistic regression model is developed to allow prediction of the presence of a large rock in future samples. Section 5.5 tests a new data set of rock samples against this model, and shows that the sample can be classified according to the presence of a large rock correctly in 93.99% of scans.

5.1 Experimental Design

The basic design for experiments in this Chapter is to fill a large wooden box with a mixture of fractured ore and various inclusion, simulating a drawpoint in an underground mine. The wooden box is shown from various angles in Figures 50-55. The box measured internally 2340 mm long, 1130 mm wide, and a maximum depth of 1200 mm. To facilitate ease of filling with the ore sample, and to create a uniform ore depth, a front panel was added to the box which reduced the depth of the ore to about 600 mm.

Baseline radar scans were recorded through the large box filled with about 2000 kg of rubble. The rubble used was generally small pieces of ore up to about 100 mm in diameter. Figure 50 shows a sample of the rubble in the box, the vertical graduations on the front being 100 mm apart horizontally. For each data set, the same ore samples were removed completely and replaced randomly in the box.

Various inclusions were then buried into the rubble at different times and radar scans recorded. A single large piece of ore was selected to represent an oversized fragment in the simulated drawpoint. The large fragment is approximately 600 mm x 600 mm x 300 mm. The large rock is shown in Figure 51 prior to backfilling with ore.

While the large fragment used in these experiments was a single large fragment, there could be situations where a number of close fitting fragments may appear as an oversized fragment. If detected as an oversized fragment, this scenario would represent a false positive prediction. In order to test this scenario, fragments over 250 mm diameter were placed in close proximity to form an object roughly 600 mm x 600 mm x 600 mm as shown in Figure 52.

To simulate air pockets within the pile, two structures were used. A hidden air pocket was simulated by using an air-filled plastic barrel, buried within the rubble. Figures 53 shows the barrel in position before it was buried, and Figure 54 shows the barrel almost buried by rubble.
Figure 50: Ore fragments up to about 100 mm were the base case 'Rubble' for the experiments conducted.

Figure 51: The large fragment prior to burying in rubble.
Figure 52: Close fitting fragments may resemble a large rock.

Figure 53: The plastic barrel simulating an air pocket within the rubble.
5.1. EXPERIMENTAL DESIGN

Figure 54: The plastic barrel buried in the rubble.

<table>
<thead>
<tr>
<th>Method</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>time</td>
<td>signal propagation time through the medium</td>
</tr>
<tr>
<td>2</td>
<td>tAtt</td>
<td>attenuation of amplitude in the time domain (equation (21))</td>
</tr>
<tr>
<td>3</td>
<td>eAtt</td>
<td>attenuation of signal energy in the frequency domain (equation (23))</td>
</tr>
<tr>
<td>4</td>
<td>Q_{peak}</td>
<td>Q measurement using peak frequency downshift [102] (Bradford’s equation (29))</td>
</tr>
<tr>
<td>5</td>
<td>Q_{cent}</td>
<td>Q measurement using Bradford’s equation, but using the centroid frequency rather than peak frequency</td>
</tr>
<tr>
<td>6</td>
<td>Q_{cfds}</td>
<td>Q measurement using centroid frequency downshift [84] (equation (28))</td>
</tr>
</tbody>
</table>

It is expected that the surface of a rock pile would not be as uniform as in the laboratory. It is likely that there would be irregularities in the actual surface which may be like large divots. To simulate this occurrence, the barrel was removed leaving a large crater in the surface as shown in Figure 55.

A further data set contained rubble with a steel roof bolt embedded to test if a conductive contaminant would influence the results.

The rock samples itemised above were tested using the radar system described in Section 3.2. For each sample, Table 8 lists the velocity and attenuation methods described in Chapter 4 and used for the following experiments.

All statistical calculations were performed using the R language (version 3.0.2) [116]. An
Figure 55: After removing the plastic barrel, a large crater remained. This simulated an irregular surface of the ore at the drawpoint.
5.1. EXPERIMENTAL DESIGN

Abridged version of the statistical results are included in this chapter. Full statistical output from R can be downloaded from http://csusap.csu.edu.au/~abenter/research.

All signal processing was carried out using GNU Octave (version 3.6.4) [117]. Full code listings for all developed code are included in Appendix A.

5.1.1 Dataset Description

The SiroPulseII system, as previously documented, was used to capture signal data. The antennas were placed on either side of the box for trans-illumination scanning, as shown previously in Figure 34.

Radar data was captured through the empty box to determine whether the location of the box within the laboratory, or the direction of scanning, had any effects upon the signal. The box was located in two positions within the laboratory. Initially the box was positioned parallel to an external brick wall within the laboratory, with a minimum of 500 mm clearance around the box to allow access to all sides. Later the box was moved into the middle of the room at an angle of approximately 45 deg to the wall. Again, a minimum clearance of about 500 mm was maintained to any structure to allow access around the box.

For all radar scans, the recordings were made along the short horizontal axis of the box. The distance between the antennas was 1190 mm.

Data was recorded in two directions through the box without changing the material – labelled as "Forward" and "Reverse". The labels have no other meaning than to indicate they were in opposing directions. If the nearby walls or furniture had any effect on the radar signal, these would appear as a discernible difference, particularly when comparing the forward and reverse scans.

The box was marked with 22 vertical slices through the long side of the box, each 100 mm apart and starting 100 mm from the ends of the box. These graduations can be seen in Figure 50 and Figure 55. The antenna was positioned at three heights on each of these slices – 140 mm, 290 mm and 325 mm above the concrete floor.

The datasets used for statistical analysis were:

**Dataset 1:** (264 scans) the empty box was used in Section 5.2. As the name suggests, this data was through the empty wooden box. Analysis of this data was used to determine
any effects from the box, or from the location of the box in the laboratory.

**Dataset 2:** (132 scans) contained only small rubble pieces of up to 100 mm diameter as previously described. This data set was used to analyse the data recorded through the ore material to determine any effects from the position of the antenna in relation to the box.

**Dataset 3:** (144 scans) contained rubble together with a large fragment with dimensions approximately 600 mm x 600 mm x 300 mm. The large fragment was situated between slices 10–15 and completely surrounded by rubble. The rock was placed roughly central in the scan line, allowing approximately 300 mm of rubble in front of, and behind, the rock. These samples have been identified as 'Rock' in the discussion below.

**Dataset 4:** (276 scans) contained the same large rock as used in Dataset 3. It also contained a number of other inclusions which might be expected to appear at a drawpoint. These included a large rock, a plastic barrel simulating an air pocket, a surface crater, intermediate sized fragments that might appear as a large rock and a roof bolt embedded in rubble. Descriptions and photographs for the inclusions are shown in Figures 51–55.

### 5.2 The Empty Box

Tables 9 and 10 shows the mean values for each metric and the P-value for the t-test. As the P-values were greater than 0.05, the null hypothesis \( H_0 : \mu_a - \mu_b = 0 \) is not rejected and so can conclude that the means were equal for both directions and both locations. Hence, for the empty box there was no significant effect from the location or direction of recording.

### 5.3 Rubble Base-Case

The box was filled with a rubble-only mixture, previously identified as Dataset 2. This mixture was used for the remaining experiments as the background material into which the inclusions were placed. As such, this mixture represents the *base-case* material.
5.3. RUBBLE BASE-CASE

Table 9: Effect of recording 'Direction' on the signal.

<table>
<thead>
<tr>
<th>Method</th>
<th>Forward (mean)</th>
<th>Reverse (mean)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>3.563</td>
<td>3.573</td>
<td>0.393</td>
</tr>
<tr>
<td>tAtt</td>
<td>24.472</td>
<td>24.896</td>
<td>0.180</td>
</tr>
<tr>
<td>eAtt</td>
<td>25.689</td>
<td>25.962</td>
<td>0.363</td>
</tr>
<tr>
<td>Q_{peak}</td>
<td>-9.980</td>
<td>-10.717</td>
<td>0.838</td>
</tr>
<tr>
<td>Q_{cent}</td>
<td>13.310</td>
<td>134.153</td>
<td>0.461</td>
</tr>
<tr>
<td>Q_{cfds}</td>
<td>44.866</td>
<td>215.216</td>
<td>0.449</td>
</tr>
</tbody>
</table>

Table 10: Effect of recording 'Location' on the signal.

<table>
<thead>
<tr>
<th>Method</th>
<th>Middle (mean)</th>
<th>Wall (mean)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>3.569</td>
<td>3.567</td>
<td>0.826</td>
</tr>
<tr>
<td>tAtt</td>
<td>24.782</td>
<td>24.586</td>
<td>0.534</td>
</tr>
<tr>
<td>eAtt</td>
<td>25.970</td>
<td>25.681</td>
<td>0.334</td>
</tr>
<tr>
<td>Q_{peak}</td>
<td>-11.587</td>
<td>-9.109</td>
<td>0.491</td>
</tr>
<tr>
<td>Q_{cent}</td>
<td>15.559</td>
<td>131.904</td>
<td>0.478</td>
</tr>
<tr>
<td>Q_{cfds}</td>
<td>57.812</td>
<td>202.270</td>
<td>0.521</td>
</tr>
</tbody>
</table>
Radar data was captured along the 22 slices through the box. Each slice represented a straight line, zero offset profile scan through the material, as the receive antenna was positioned at the same height as the source antenna.

Table 11, column 2, shows the result of these scans to determine any effects from the position of the antenna. Although there was no significant difference in the time metric for each slice, there was a significant difference recorded (P < 0.05) for all other metrics used. A TukeyHSD comparison revealed that the scans that represent a significant difference are slices 1, 2, 21 and 22. These slices were closest to the edges of the box, allowing the signal to bleed around the sides and through air. This agrees with the suggestion in the previous chapter that the broad beam width of the radar signal was bleeding around the sides of the smaller crates.

After removing the edge slices 1, 2 and 21, 22 each data set of material then comprised 18 scans. There was no significant difference between the means of each slice through the empty box for time (p=0.221), time domain attenuation (tAtt) (P=0.054), energy attenuation (eAtt) (P=0.092), Qpeak (p=0.067) and Qcfds (p=0.251). As the P-values are greater than 0.05, the null hypothesis cannot be rejected and so can conclude that the means are equal for all slices through the empty box. The metric Qcent (P < 0.001) is still significantly different between slices, however as will be shown in Section 5.5, Qcent will not be used for any prediction models.

Each data set was also recorded at three heights. The transmit and receive antennas were set at a height of 140 mm, 290 mm and 355 mm above the ground level.

A TukeyHSD comparison showed that there was a difference between the 140 mm height and both the 290 mm and 355 mm heights (columns 12 and 3 in Table 12). There was, however, no significant difference between the 290 mm and 355 mm data (column 4 in
### 5.4 Training Data

The baseline results for the empty box show that there was no need to differentiate data based on the direction or location. There was also no significant difference between the scans recorded at heights 290 mm and 355 mm above the floor.

Data recorded near the edges of the box, however, were affected such that they were significantly different from the remaining scans. Data recorded in slice 1, 2, 21 and 22 experienced bleeding around the sides and were significantly different to the remaining slices. Accordingly, slices 1, 2, 21 and 22 were excluded from the data sets used in the remaining statistical analysis.

Data recorded at a height of 140 mm was likely affected by the proximity of the concrete floor, similar to the bleeding around the sides of the box. Further testing would be required to establish the minimum height required. For the remaining analysis, data recorded at a height of 140 mm was excluded from the data sets.

A sample of the recorded data is included in Table 13.

A subset of Dataset 4 has been used as a training set for the calculation of the model used for prediction. Half of these scans were extracted from the dataset to create a new set – *training* – used to develop a logistic model. The remaining scans from Dataset 4 were combined with Dataset 3 to create a new set to test the prediction model.

---

**Table 12: Effect of the 'Height' of the antennas on the signal.**

<table>
<thead>
<tr>
<th>Method</th>
<th>140–290 mm P-value</th>
<th>140–355 mm P-value</th>
<th>290–355 mm P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>time</em></td>
<td>0.011</td>
<td>&lt; 0.001</td>
<td>0.235</td>
</tr>
<tr>
<td><em>tAtt</em></td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.356</td>
</tr>
<tr>
<td><em>eAtt</em></td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.157</td>
</tr>
<tr>
<td><em>Q</em>&lt;sub&gt;peak&lt;/sub&gt;</td>
<td>0.109</td>
<td>0.989</td>
<td>0.145</td>
</tr>
<tr>
<td><em>Q</em>&lt;sub&gt;cent&lt;/sub&gt;</td>
<td>&lt; 0.001</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td><em>Q</em>&lt;sub&gt;cdfs&lt;/sub&gt;</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Table 12) for time, amplitude attenuation, energy attenuation and *Q*<sub>cdfs</sub>, as shown in Table 12. The metric *Q*<sub>cent</sub> was still significantly different between these heights, however as will be explained in Section 5.5, *Q*<sub>cent</sub> was not be used for any prediction models.
# CHAPTER 5. LARGE ROCK DETECTION

Table 13: Subset of all recorded data.

<table>
<thead>
<tr>
<th>Material</th>
<th>time</th>
<th>tAtt</th>
<th>eAtt</th>
<th>Q(_{\text{peak}})</th>
<th>Q(_{\text{cent}})</th>
<th>Q(_{\text{cfd}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubble</td>
<td>6.815</td>
<td>34.222</td>
<td>26.503</td>
<td>7.333</td>
<td>8.437</td>
<td>4.837</td>
</tr>
<tr>
<td>Rubble</td>
<td>7.870</td>
<td>33.744</td>
<td>27.372</td>
<td>10.269</td>
<td>12.214</td>
<td>6.884</td>
</tr>
<tr>
<td>Rubble</td>
<td>6.780</td>
<td>34.364</td>
<td>28.031</td>
<td>7.159</td>
<td>10.488</td>
<td>5.690</td>
</tr>
<tr>
<td>Rubble</td>
<td>7.483</td>
<td>37.891</td>
<td>31.916</td>
<td>7.774</td>
<td>12.284</td>
<td>7.092</td>
</tr>
<tr>
<td>Rock</td>
<td>7.623</td>
<td>42.892</td>
<td>35.433</td>
<td>10.144</td>
<td>13.296</td>
<td>11.212</td>
</tr>
<tr>
<td>Rock</td>
<td>7.166</td>
<td>50.159</td>
<td>42.890</td>
<td>9.536</td>
<td>14.353</td>
<td>17.284</td>
</tr>
<tr>
<td>Rock</td>
<td>8.713</td>
<td>49.220</td>
<td>42.097</td>
<td>11.856</td>
<td>19.312</td>
<td>20.691</td>
</tr>
<tr>
<td>Rock</td>
<td>7.448</td>
<td>34.319</td>
<td>29.945</td>
<td>22.887</td>
<td>18.918</td>
<td>10.413</td>
</tr>
<tr>
<td>Rubble</td>
<td>7.448</td>
<td>29.184</td>
<td>25.217</td>
<td>10.399</td>
<td>17.405</td>
<td>8.571</td>
</tr>
<tr>
<td>Rubble</td>
<td>6.815</td>
<td>33.057</td>
<td>25.306</td>
<td>8.281</td>
<td>11.023</td>
<td>6.142</td>
</tr>
</tbody>
</table>
5.4. TRAINING DATA

In total, 139 scans in the training dataset were used to compare the different rock samples. Table 14 shows the mean value for each metric over each sample type. Distributions are also shown in the box plots [118] for each metric in Figures 56–61.

**Time Analysis – time** For the signal time to propagate through the samples, Analysis of Variance (ANOVA) suggests there was a statistically significant difference in the means (P < 0.001) of each material. Figure 56 shows the boxplot for the time the signal took to propagate through the samples. The three samples on the right – Fragments, Rock and Rubble – were all rock samples and were quite different from the air samples – Barrel and Crater.

Using TukeyHSD, there was a significant difference between the ore samples (Rock, Rubble, Fragments) and the air samples (Crater, Barrel) suggesting time could be a useful measure of the amount of rock. This confirms the use of velocity in earlier experiments, particularly with regard to permittivity estimation. As previously demonstrated, the permittivity is related to bulk density. The higher permittivity of the rock slows the signal down so that the arrival time is delayed. In samples with more air (lower bulk density) the signal will be faster.
CHAPTER 5. LARGE ROCK DETECTION

Figure 57: Boxplot of the mean attenuation ($t_{Att}$) of the signal in the time domain.

Figure 58: Boxplot of the mean energy attenuation ($e_{Att}$) of the signal after propagating through the box.
5.4. TRAINING DATA

Figure 59: Boxplot of the mean $Q_{\text{peak}}$ using the Bradford’s measure of peak frequency.

Figure 60: Boxplot of the mean $Q_{\text{cent}}$ using the modified Bradford method of centroid frequency.
Figure 61: Boxplot of the mean $Q_{cfds}$ using the centroid frequency downshift method.

Table 14: Sample Means

<table>
<thead>
<tr>
<th>Method</th>
<th>Bar (mean)</th>
<th>Barrel (mean)</th>
<th>Crater (mean)</th>
<th>Fragments (mean)</th>
<th>Rock (mean)</th>
<th>Rubble (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$time$</td>
<td>7.27</td>
<td>5.82</td>
<td>6.22</td>
<td>7.53</td>
<td>8.08</td>
<td>7.35</td>
</tr>
<tr>
<td>$tAtt$</td>
<td>35.17</td>
<td>41.12</td>
<td>38.69</td>
<td>40.91</td>
<td>42.47</td>
<td>35.89</td>
</tr>
<tr>
<td>$eAtt$</td>
<td>31.21</td>
<td>38.35</td>
<td>35.20</td>
<td>37.28</td>
<td>40.54</td>
<td>32.23</td>
</tr>
<tr>
<td>$Q_{peak}$</td>
<td>6.43</td>
<td>22.14</td>
<td>24.78</td>
<td>7.44</td>
<td>12.82</td>
<td>7.98</td>
</tr>
<tr>
<td>$Q_{cent}$</td>
<td>14.77</td>
<td>17.90</td>
<td>23.04</td>
<td>15.04</td>
<td>17.92</td>
<td>15.09</td>
</tr>
<tr>
<td>$Q_{cfds}$</td>
<td>8.02</td>
<td>12.26</td>
<td>12.64</td>
<td>12.16</td>
<td>15.24</td>
<td>9.68</td>
</tr>
</tbody>
</table>
Between the ore samples, there was a significant difference between Rock and Rubble. The rock sample was not, however, significantly different to the fragments (P=0.063). In order to detect the difference with fragments an additional parameter is likely to be required.

As a method of differentiating the large rock from everything else, time is likely to be a good predictor between ore and air samples.

The mean time for scans with the steel roof Bar that was placed in the rubble was not significantly different to the Rubble, suggesting the Bar was not detectable using velocity/time measurements.

**Amplitude Attenuation Analysis – \( t_{Att} \)** Amplitude attenuation measures the signal loss over time in the main pulse that arrives at the remote antenna. Figure 57 shows boxplot for amplitude attenuation in the time domain over the samples. While there was a significant difference in the means for rock–rubble (\( P < 0.001 \)), and also rock–crater (\( P < 0.001 \)), there was no significant difference between the mean attenuation of rock–barrel (\( P=0.740 \)) nor rock–fragments (\( P=0.459 \)).

Unlike velocity, there was not a clear distinction between the ore samples (rock, rubble and fragments) and air samples (barrel and crater), suggesting the amplitude attenuation may not be a good predictor variable.

There was no significant difference in amplitude attenuation means between rubble–bar (\( P=0.968 \)) suggesting that amplitude attenuation is also not suitable to detect the presence of a steel bar.

**Energy Attenuation Analysis – \( e_{Att} \)** The mean energy attenuation comparison exhibits only a few sample means that were similar (see Figure 58). Rubble was significantly different to all other ore and air samples (\( P < 0.001 \)), suggesting energy attenuation may be a good predictor to isolate rubble samples. Similarly, the scans through the crater (surface irregularity) were also significantly different to the rock and rubble scans (\( P < 0.001 \)).

The mean energy attenuation through rock scans was not significantly different to the barrel scans (\( P=0.281 \)), however in combination with another variable, energy attenuation might prove a useful predictor.

Once again there was no difference between the bar and rubble suggesting the bar is not detectable using energy attenuation.
**Q Analysis**  The comparison of $Q_{\text{peak}}$ (Figure 59) in the scans showed that every measure excepting fragments–crater (P=0.041) and rubble–crater (P=0.004) were not significantly different. $Q_{\text{peak}}$ is therefore likely to be a poor indicator for detecting large rocks.

$Q_{\text{cent}}$ gave similar results as $Q_{\text{peak}}$ with the addition of crater–bar being significant (P=0.007). As these do not improve the detection of a large rock, $Q_{\text{cent}}$ is also likely to be a poor indicator.

$Q_{\text{cfds}}$ showed a similar comparison of means as $Q_{\text{peak}}$ and $Q_{\text{cent}}$, except that the comparison between rubble–rock was significantly different (P < 0.001). This makes $Q_{\text{cfds}}$ a possible metric for detection of the big rock as it will likely add to the determination between rubble and rock scans.

**Predictor variables**  From the analysis of means using TukeyHSD multiple mean comparison, three possible predictor variables have been identified:

- $time$ – signal velocity
- $eAtt$ – signal energy attenuation
- $Q_{\text{cfds}}$ – centroid frequency downshift

As previously mentioned, the purpose of this research is to identify when a large fragment is present. Accordingly, the predictor variable(s) are required to determine only a ‘Yes|No’ answer on whether a large rock is present, rather than trying to identify the actual rock sample. There is no interest in determining if the sample is ‘Rubble’ or contains intermediate sized fragments. We are only interested in the determination of whether a large fragment is present.

A logistic regression can be used with such ‘Yes|No’ data when a prediction is required. The current training data set is extended to include a binary field ‘rock’ where ‘1’ indicates a large rock was present, and ‘0’ indicates a large rock was not present.

A full logistic regression model was calculated for the expanded training data using all metrics. As demonstrated in the previous comparison analysis, not all metrics were found to make a significant contribution to the model. Hence, a reduced model could be used. Further model calculations established that the metrics $time$, $eAtt$ and $Q_{\text{cfds}}$ as identified above in the individual mean analysis were all statistically significant (P < 0.05).

A logistic regression model allows the prediction of the probability of the dependent variable. In this case, the model allowed prediction of whether a scan was through a large
5.4. TRAINING DATA

Table 15: Logistic Regression Model

<table>
<thead>
<tr>
<th>Model</th>
<th>coef.</th>
<th>exp(coef.)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-40.89</td>
<td>0</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>time</td>
<td>2.01</td>
<td>7.45</td>
<td>0.002</td>
</tr>
<tr>
<td>eAtt</td>
<td>0.71</td>
<td>2.04</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Q_{cfds}</td>
<td>-0.22</td>
<td>0.81</td>
<td>0.016</td>
</tr>
</tbody>
</table>

The greatest indicator of a rock being present is the time the signal takes to travel through the material (\(time\)). As time increases, the odds that the sample includes a large rock increases by a factor of 7.45 for every nanosecond longer it takes to travel through the sample. As already discussed though, this is insufficient on its own to differentiate between Rock and Fragments.

Energy attenuation (\(eAtt\)) measures the total signal loss over the 0 GHz to 3 GHz band on a time window surrounding the arrival peak. As energy attenuation (\(eAtt\)) increases, the odds a rock is in the sample increases by a factor of 2.04. This suggests that increased dispersion of the signal is caused by the large rock fragment.

The Q measurement has an inverted affect upon the prediction. As \(Q_{cfds}\) increases, the probability the sample includes a large rock decreases. This reflects the relationship between Q and loss described in Section 2.4.1 where higher Q values are associated with lower energy loss.

The attenuation results show that as attenuation increases, measured either by high energy attenuation or smaller Q value, the probability the sample contains a large rock increases.
5.5 Detecting Big Rocks

Based on the training dataset containing 139 scans, a logistic model was generated to predict whether a large rock was present. This model was applied to a different dataset ‘testdata’ containing 283 scans as described in Section 5.1.1.

The model predicted the probability that the scan was through a sample containing a large fragment. The calculated probability was then compared to the known case for each scan. Table 16 shows the percentage of correctly identified samples at different threshold values which is also shown in Figure 62. The percentage of correct predictions quickly passes 90% at a threshold value of 0.15 reaching a maximum of 93.99% at threshold of 0.55.

An optimum threshold value is, however, a trade-off between correct values and the amount of false negatives and false positives. A false positive is when the model indicates a large rock is present, when in fact it is not. A false negative would indicate that while a large rock is present, it is not detected. Arguably, the number of false negatives are of more concern as it is these situations where a large fragment may be collected by the LHD and impact upon crusher operations.

The number of false negatives increased throughout the threshold range 0–1. At a threshold

Figure 62: Graph of prediction threshold and percentage of correct (green), false negative (red) and false positive (orange) results.
### Table 16: Rock prediction over Dataset 'testdata' 

<table>
<thead>
<tr>
<th>Threshold (prob.)</th>
<th>Correct (%)</th>
<th>False-Negative (%)</th>
<th>False-Positive (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>14.13</td>
<td>0.00</td>
<td>85.87</td>
</tr>
<tr>
<td>0.05</td>
<td>85.51</td>
<td>2.47</td>
<td>12.01</td>
</tr>
<tr>
<td>0.10</td>
<td>89.40</td>
<td>3.53</td>
<td>7.07</td>
</tr>
<tr>
<td>0.15</td>
<td>91.17</td>
<td>4.24</td>
<td>4.59</td>
</tr>
<tr>
<td>0.20</td>
<td>92.58</td>
<td>4.24</td>
<td>3.18</td>
</tr>
<tr>
<td>0.25</td>
<td>92.58</td>
<td>4.59</td>
<td>2.83</td>
</tr>
<tr>
<td>0.30</td>
<td>92.93</td>
<td>4.95</td>
<td>2.12</td>
</tr>
<tr>
<td>0.35</td>
<td>93.29</td>
<td>4.95</td>
<td>1.77</td>
</tr>
<tr>
<td>0.40</td>
<td>93.64</td>
<td>4.95</td>
<td>1.41</td>
</tr>
<tr>
<td>0.45</td>
<td>93.29</td>
<td>5.30</td>
<td>1.41</td>
</tr>
<tr>
<td>0.50</td>
<td>93.64</td>
<td>5.30</td>
<td>1.06</td>
</tr>
<tr>
<td>0.55</td>
<td>93.99</td>
<td>5.30</td>
<td>0.71</td>
</tr>
<tr>
<td>0.60</td>
<td>93.64</td>
<td>5.65</td>
<td>0.71</td>
</tr>
<tr>
<td>0.65</td>
<td>93.64</td>
<td>5.65</td>
<td>0.71</td>
</tr>
<tr>
<td>0.70</td>
<td>93.29</td>
<td>6.01</td>
<td>0.71</td>
</tr>
<tr>
<td>0.75</td>
<td>93.64</td>
<td>6.01</td>
<td>0.35</td>
</tr>
<tr>
<td>0.80</td>
<td>91.87</td>
<td>7.77</td>
<td>0.35</td>
</tr>
<tr>
<td>0.85</td>
<td>90.81</td>
<td>8.83</td>
<td>0.35</td>
</tr>
<tr>
<td>0.90</td>
<td>90.11</td>
<td>9.54</td>
<td>0.35</td>
</tr>
<tr>
<td>0.95</td>
<td>89.40</td>
<td>10.25</td>
<td>0.35</td>
</tr>
<tr>
<td>1.00</td>
<td>85.87</td>
<td>14.13</td>
<td>0.00</td>
</tr>
</tbody>
</table>
value of 0.15, the number of false negatives was 4.24%, closely matching the false positive reading (4.59%). At the peak in correct readings (threshold = 0.55), false negatives has increased to 5.3% and false positives fallen to 0.71%.

What is apparent from Figure 62 is that the number of correct determinations based on the model was very stable across the threshold range of 0.2–0.75 staying above 92% correct determinations. This leaves scope for the mine operator to set the appropriate threshold based on the desired level of false negative and false positives.

5.6 Conclusion

This chapter described a medium-scale experiment for determining the characteristics of various rock samples using GPR. The metrics identified in Chapter 4 were applied to the same rock data. The big box resolved the problem identified in Chapter 4 where the signal was able to bleed around the edges of the crate and contaminate the signal.

Using bigger samples and rocks, the attenuation of various signal characteristics (amplitude, energy, Q) were tested. Analysis of the mean values identified 4 possible metrics which could be used to determine whether a big rock was present in a sample.

A logistic regression model was generated over a training set containing all sample types (rock, air pocket, rubble, crater, fragments and steel bar). This model was then tested on a different dataset containing the same inclusions. The model was able to predict correctly in 93.99% of scans whether the sample contained a large rock. Through adjustment of the threshold value, the ratio of false negative and false positive predictions can be adjusted to suit the mine operator.

This chapter has shown that it is possible to predict the presence of a large fragment in a rock pile. The method as described could be constructed as part of the drawpoint infrastructure, providing protection for the antennas. Processing is fast and computationally inexpensive. Further experiments at a full scale, underground drawpoint are necessary to resolve any engineering aspects to the installation of such a measuring tool at an operational mine.
Chapter 6

Conclusion

Before this thesis, the only method available to detect large rocks at the drawpoint were visual methods relying on the large rock being on the surface of the rock pile. Any large rocks buried within the rock pile were not detectable using computer vision or operator’s visual inspections.

The central question posed at the beginning of this thesis was:

Can oversized fragments buried in rock piles be detected?

The solution to the central question also needed to be compatible with the underground mining operations. In particular, time constraints on detection were governed by the minimum time for an LHD vehicle to return to the drawpoint. The detection system also need to be suitable to be installed at the underground mine operations within operational and engineering requirements. These requirements were posed as two additional questions:

1. Can a determination be made as to the presence of a large fragment given the time constraints of the mine?

2. Can a detection system be designed such that it would be suitable for installation within an underground mine?

Chapter 3 outlined results of ground penetrating radar image acquisition and analysis techniques to generate 2D images of the rock pile to enable detection of large rocks buried beneath the surface. While demonstrating that imaging of rock piles was possible using GPR, this method did not adequately answer the questions of operational and engineering requirements.
Generating 2D images using a GPR system capturing reflective data required the placement of the antennas on a carrier vehicle. The LHD loaders were unsuitable due to the difficulties with antenna placement. Places where the antennas would be safe from damage were limited to areas behind steel (conductive) structures which would block the electromagnetic signal from reaching the rock pile. Additional vehicles in the operational sections of the mine are undesirable due to the possibility of collisions with the LHDs during extraction operations. Scanning mechanisms would also likely be too fragile and/or lack the manoeuvrability required to navigate the tunnels of an underground mine.

The results from these experiments did show that the GPR signal could penetrate the material effectively, and that signal velocity and attenuation were affected by the rock material and could be exploited to detect large rocks.

The central question:

**Can oversized fragments buried in rock piles be detected?**

was thus addressed by resolving a number of subsidiary questions:

3. **Is there a difference in the electromagnetic signal between fragmented rock and solid rock?**

4. **Is there a relationship between the ore sample’s constitutive characteristics and the bulk density of the ore?**

Small scale and medium scale experiments described in Chapter 4 showed that there was a measurable difference between the electromagnetic signal from a solid, large rock and that from fragmented rock. A number of signal metrics were identified that showed a statistically significant difference between responses from a rock pile with a large solid rock buried within, and a rock pile with no such rock.

Velocity has been shown previously to be a reliable estimate of permittivity in fine grained and pulverised material. This thesis has shown that in variably sized and irregularly shaped fragmented material the same relationships between permittivity and velocity hold.

Permittivity has also previously been shown to be a reliable method of measuring bulk density in pulverised material. This thesis has shown that permittivity is also a reliable
measure of bulk density of fragmented rock samples over various fragment sizes and densities.

To automate the measurement of velocity through the fragmented ore, this thesis has shown a fast and reliable method of measuring signal velocity using the Hilbert Transform as a method of detecting ground penetrating radar signal arrival times.

Signal energy attenuation in the frequency domain was shown to be an effective discriminator between solid rock and fragmented rock. The measure of attenuation in the energy of a signal differed between solid rock and all fragmented rock samples.

The Quality factor Q is a measure of the frequency dependence of signal attenuation. As Q decreases, so attenuation of higher frequencies increases. This causes a measurable downshift in the spectrum. A number of methods have been detailed previously using the peak frequency or centroid frequency as the metric. This thesis has shown that for fragmented rock, the Centroid Frequency Downshift method by [99] is a significant measure between rubble and a large rock fragment.

Using a Ground Penetrating Radar unit to measure signal changes, a logistic regression model was developed which has been shown to correctly identify whether a rock is present in over 93% of the scans from a test dataset. The model parameters were established through a training set of scans that included not only a large fragment, but also features that might be expected at the drawpoint such as intermediate sized fragments, air pockets and an irregular surface. This model was then tested on an independent set of scans to determine accuracy and robustness of the measurements.

The results presented allow the central question:

**Can oversized fragments buried in rock piles be detected?**

to be answered by the following statement:

**Large rocks buried in a rock pile can be detected and differentiated from smaller rock fragments, air pockets and irregular surfaces using a ground penetrating radar to measure signal velocity and attenuation.**

This thesis has demonstrated an effective and accurate method of determining if a large rock is buried in a rock pile. The solution, however, has always needed to be able to resolve the contents of the rock pile in a suitable time frame. The method demonstrated in Chapter 5 is a fast and computationally inexpensive method of measuring a rock pile. Similarly, the method must be suitable for installation in an underground mine. While
the antennas used in the test are considered too delicate for underground installation, discussions with GPR manufacturers identified a suitable slot antenna which would be robust for underground installation. Thus, the method outlined in Chapter 5 also resolved the operational and engineering requirements outlined above.

Along the way toward an effective and suitable rock detection system, this thesis also developed a number of other methods which would be useful for GPR analysis.

Ground Penetrating Radar has proven to be an effective tool for subsurface imaging. A number of problems however affect the collection and interpretation of GPR images across many application areas. Fundamentally, GPR is a broad beam width imaging system, identifying subsurface features as a reflective imaging system. Due to the beam width, reflections arise from objects located a considerable distance laterally from the antenna. This problem is exaggerated as depth to the objects increase.

This thesis has demonstrated a new method of removing these lateral reflections through the physical motion of the antenna. The Vertical Offset Filter provides a simple and physical filtering technique which can improve the contrast of subsurface images by removing reflections from objects offset from the antennas.

When separated antennas are employed to capture signals, a problem arises with determining when time zero occurs in the receive antenna time domain. Time zero drift is a recognised problem that affects spatially separate antenna systems. Previous methods to correct for the drift have involved maintaining a record of scan times so that the drift can be calculated and compensated post-capture. A simple solution to this problem has been demonstrated in this thesis by utilising a second antenna to record the time zero at the source, allowing the signal occurrences in the time domain to be interpreted relative to the second antenna, rather than as an absolute time position.

6.1 Further Research

The large rock detection method demonstrated has provided a clear solution to the central question posed in Chapter 1. There are, however, further areas of research that have been identified but were beyond the scope of this thesis.
6.1. **FURTHER RESEARCH**

The Vertical Offset Filter discussed in Section 3.4 improved GPR image contrast by removing lateral reflections using the motion of the antenna. The algorithm currently decimates the signal in rejecting offset reflections and this could be improved to retain reflection amplitudes from objects beneath the antennas. Further work is required to refine the operation of the algorithm and to determine the resolution achievable under operational parameters.

The Quality factor Q measures the total attenuation for the medium. Part of that attenuation can be attributed to the intrinsic characteristics of the rock, and also to scattering from medium sized particles. A measure of scattering that could determine fragmentation size distributions would be a useful addition to the demonstrated remote measuring techniques.

Chapter 4 also demonstrated partial results showing a relationship between fragment size and attenuation. This could be used to measure post-crusher fragments as a conveyor monitoring system, which would alleviate the need for additional lighting and laser systems to analyse fragmentation post-crusher and pre-mill.

The method presented for large fragment identification has been demonstrated to mining engineers from the sponsor company and forms the central research to a new sponsored research project investigating rock densities in the drawbell. Looking further inside the drawbell allows advanced knowledge of the appearance of large boulders as they approach the drawpoint. This provides an opportunity to modify scheduling around predicted arrivals rather than interruptions to production when boulders actually arrive at the drawpoints.
Bibliography


Appendix A

Octave Code

csuAnalysis.m

This script performs the main calculations used in the prediction of the presence of a rock. This script utilises the function positiveFFT.m to calculate the normalised Fast Fourier Transform available from [119].

```matlab
function [dt, att, eAtt, Qpeak, Qcent, Qcfs] = csuAnalysis( filename, flag )

% read in file
[reflS, propS, Fs] = csuSignal(filename);
data(:,1) = reflS;
data(:,2) = propS;
data(:,3) = hilbert(data(:,1));
data(:,4) = hilbert(data(:,2));

% calculate time using Hilbert peak
[peak, send] = max(abs(data(:,3)));
/trans, recv] = max(abs(data(send+80:512,4)));
recv = recv + send + 79;
timebase = 512e9/Fs;
dt = timebase/512*(recv-send);
% add offset to send antenna
dt = dt + 0.1;

% calculate attenuation
[rpeak, temp] = max(data(:,1));
[ppeak, temp] = max(data(:,2));
att = 20*log10(rpeak/ppeak);

% calc FFT
```
if (send < 50)
    start = 1;
    finish = 150;
else
    start = send - 50;
    finish = send + 100;
endif
sendTrim = data(start:finish,1);
for sm=size(sendTrim,1)+1:512
    sendTrim(sm,1) = 0;
end;
[fftRF, rf] = positiveFFT(sendTrim,Fs);
start2 = recv - 50;
recvTrim = data(start2:512,2);
for pm=size(recvTrim,1)+1:512
    recvTrim(pm,1) = 0;
end;
[fftPF, pf] = positiveFFT(recvTrim,Fs);
scale = 1000 / max(abs(fftRF));
fftRF = fftRF.*scale;
fftPF = fftPF.*scale;
llimit = 1;
ulimit = 1;
while (pf(ulimit) < 3e9)
    ulimit = ulimit + 1;
endwhile;
ulimit = ulimit - 1;

% calc sum of Magnitude
mag = sum(abs(fftPF(llimit:ulimit)));

% calc energy
eRF = sum(abs(fftRF(llimit:ulimit).^2));
ePF = sum(abs(fftPF(llimit:ulimit).^2));
eAtt = 10 * log10(eRF/ePF);

% calc Q - peak
[peak, rpeak] = max(fftRF);
frF = rf(rpeak);
[peak, ppeak] = max(fftPF);
if (rpeak == ppeak)
    ppeak = ppeak - 1;
\[ P_F = p_f(p_{peak}); \]
\[ w_{20} = (2*\pi*f_RF)^2; \]
\[ w_{2t} = (2*\pi*f_PF)^2; \]
\[ w_t = (2*\pi*f_PF); \]
\[ t = dt/1000000000; \]
\[ top = w_{20} - w_{2t}; \]
\[ bott = w_{20} * w_t; \]
\[ invQ = (4/t) * (top / bott); \]
\[ Q_{peak} = 1/invQ; \]

\% calc Q – Centroid
\[ \text{centRF} = \text{csuCentroid}(rf, \text{fftRF}, \text{lLimit}, \text{uLimit}); \]
\[ \text{centPF} = \text{csuCentroid}(pf, \text{fftPF}, \text{lLimit}, \text{uLimit}); \]
\[ w_{20} = (2*\pi*\text{centRF})^2; \]
\[ w_{2t} = (2*\pi*\text{centPF})^2; \]
\[ w_t = (2*\pi*\text{centPF}); \]
\[ t = dt/1000000000; \]
\[ top = w_{20} - w_{2t}; \]
\[ bott = w_{20} * w_t; \]
\[ invQ = (4/t) * (top / bott); \]
\[ Q_{cent} = 1/invQ; \]

\% downshift
\[ C_{shift} = \text{centPF} - \text{centRF}; \]
\[ P_{shift} = f_RF - f_PF; \]

\%calc Q – CFS
\[ cfsPF = p_f(\text{lLimit} : \text{uLimit}); \]
\[ cfsFFT = \text{fftPF}(\text{lLimit} : \text{uLimit}); \]
\[ \text{sig} = (\text{cfsPF} - \text{centPF}).^2; \]
\[ \text{sig} = \text{sig}'; \]
\[ \text{sigVar} = \text{sum}(\text{sig} .* \text{abs}(\text{cfsFFT})) / \text{sum}(\text{abs}(\text{cfsFFT})); \]
\[ Q_{cfs} = -1 * \text{sigVar} * \pi * (C_{shift} / t)^{-1}; \]
\[ \text{disp}(Q_{cfs}); \]
\[ Q_{cfs} = -1 * (\pi * t * \text{sigVar}) / (C_{shift}); \]

if (flag == 1)
\% plot figure
\[ \text{name} = \text{strrep} (\text{filename}, "rdr", "eps") \]
\[ \text{semilogy}(\text{rf}(1:\text{uLimit+5}), [\text{abs}(\text{fftRF}(1:\text{uLimit+5})) \text{abs}(\text{fftPF} (1:\text{uLimit+5}))], 'LineWidth', 4); \]
\[ \text{xlabel}("Frequency (Hz)", 'fontName', '/usr/share/fonts/truetype/Roboto-Medium.ttf', 'FontSize', 14); \]
\[ \text{ylabel}("Amplitude", 'fontName', '/usr/share/fonts/truetype/Roboto-Medium.ttf', 'FontSize', 14); \]
csuSignal.m

The csuSignal.m script performs pre-processing steps on the raw data files from the CSIRO SiroPulseII GPR unit.

This script also calls csuRDRtime.m which reads the data from the SiroPulseII data file and stores it in an array data. csuRDRtime is a modified version of the data processing scripts provided by the CSIRO to accompany the SiroPulseII GPR unit. The original script also returned an array info containing data capture settings, including the time over which data was recorded in nanoseconds. The modified script returns timebase only.

```octave
function [reflSM, propSM, Fs] = csuSignal(filename)

% read in data file
[data, timebase] = csuRDRtime(filename);
Fs = 1e9/(timebase/512);

% process both scans
reflection = data(:, :, 1);
propagation = data(:, :, 2);

% discard first & last quarter
reflection = reflection(:, floor(size(reflection,2)*0.25):floor(size(reflection,2)*0.75));
propagation = propagation(:, floor(size(propagation,2)*0.25):floor(size(propagation,2)*0.75));

% get average scan
reflM = mean(reflection,2);
propM = mean(propagation,2);

% remove mean
ns = length(reflM);
```
dc = ones(ns,1)*mean(reflM,1);
reflZ = reflM - dc;

ns = length(propM);
dc = ones(ns,1)*mean(propM,1);
propZ = propM - dc;

% dewow
reflD = dewow(reflZ);
propD = dewow(propZ);

% smooth the data using a 7-point average
for m = 4:(length(reflD)-3)
    reflSM(m,1) = mean(reflD(m-3:m+3,1));
end;

for m = 4:(length(propD)-3)
    propSM(m,1) = mean(propD(m-3:m+3,1));
end;

% ensure sizes are the same
for m=(size(reflSM,1)+1):512
    reflSM(m,1) = 0;
end;

for m=(size(propSM,1)+1):512
    propSM(m,1) = 0;
end;