SEISMIC WHILE DRILLING IMAGING IN HARD ROCK ENVIRONMENT

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This thesis is presented for the degree of
Doctor of Philosophy
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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material, which has been accepted for the award of any other degree or diploma in any university.

Signature: 

10/16/14

Date: ________________
To my wife, Tanzhe Fu,

To my daughter, Summer Sun,

To my son, Winter Sun.
Acknowledgments

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Statement of candidate about the contribution of others
I am the main author for all the publications used as a part of this thesis. In all these papers, I am the principal investigator.
Abstract

Drill-bit Seismic-While-Drilling (SWD) is a passive seismic-imaging method, which is implemented by utilising the drill-bit vibration as a seismic source. A receiver array is generally deployed on the surface of the earth or in boreholes to capture the drill-bit signals. In an ideal situation, the passive signals are converted into a seismogram similar to Reverse Vertical-Seismic-Profiling (RVSP) using crosscorrelation. This seismic method requires no additional rig time, but provides one of the benefits of acquiring the real-time seismic data used for imaging around the bore hole.

For the application of the SWD method, the energy of the drill-bit vibration is an important factor to success, so it is understood that most successful drill-bit SWD experiments were completed with a rock-crushing roller-cone bit in petroleum industry. However, there are few successful SWD experiments performed in the mining industry, even in hard-rock applications. One of the main reasons is because of the dominant use of the diamond impregnated drill-bit, which is generally quiet while drilling. The study of this thesis focuses on application of SWD in hard-rock environments and investigates the feasibility of acquiring and utilising weak diamond drill-bit emitted signals.

To study the SWD applications in hard-rock environments, three main subjects of the research are investigated and presented in the thesis. They include:

- Investigating methods that suppress strong coherent noises generated from the rig site;

- Comparing coherent signal detection methods in terms of detectability and imaging resolution, then performing velocity analysis and imaging using the acquired drill-bit signal;

- Comparing radiated energy from different drilling methods in hard-rock environments: diamond-impregnated drilling and Reverse-Circulation drilling.
Both synthetic and field data are exploited in the studies. For the field data example, there were two experiments conducted at Brukunga and Hillside in South Australia. For the purpose of drilling signal characterisations, rig coherent noise suppression and the drill-bit imaging, the data from the Brukunga experiment were investigated. Firstly, to extract the drill-bit signal from strong rig-site noise, I demonstrate the use of Karhunen-Loéve (KL) transform to separate the possible drill-bit wavefields. I show that this method is effective and has little or no contamination from the desired drill-bit wavefield when it is applied in a SWD common receiver gather. This method is compared with f-k filter, and its advantage is demonstrated in an SWD application. Secondly, to image a diamond drill-bit with high spatial resolution using its weak wavefields, I compare different coherent signal detection methods including: semblance and Multiple Signal Classification (MUSIC). Synthetic examples are used to demonstrate the differences between the two methods. The MUSIC-coherency method manifests higher spatial resolution compared to semblance when imaging a buried unknown source. The resolution and signal detectability by MUSIC can be controlled by the signal space dimension. I show that with added coherent noise and large wavefront time-shift errors, MUSIC method still shows comparable measurement to semblance. Therefore, the MUSIC coherency method can be utilised as a good complement to semblance in terms of improved image resolution.

To understand the different level of energy radiation from different drilling techniques, I compare and analyse the energy emitted from hard-rock drilling between diamond impregnated and Reverse-Circulation (RC) drilling from the Brukunga experiment. The two drilling mechanisms generate very different seismic wavefields. From the field data, by investigating the raw data energy, frequency analysis and crosscorrelation test from the field data, the seismic responses from percussive RC drilling provide a strong indication that the drill-bit energy can be suitable for drill-bit seismic imaging purposes. It may also provide high-resolution images with bore hole seismic acquisition. In contrast, at comparable drilling conditions, the diamond-bit drilling is quiet; its energy is difficult to detect by a surface receiver array.

The techniques studied in the thesis, such as MUSIC and KL transform, can be
applied to other similar SWD experiments. Some other research topics, such as

correlation of the narrow-band drilling signal and drill-bit interferometry migration,

are also investigated in the thesis. All these studies highlight the importance of future

research for applications of SWD in mineral exploration.
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Chapter 1

Introduction

1.1 Motivation

To extract and explore resources from the Earth’s subsurface, drilling plays a key aspect in oil, gas and mineral exploration. Drilling is an expensive process due to related risks and uncertainties. This is particularly true in the oil and gas industry, where drilling rig rates for deep water in 2010 was around $420,000/day (Wikepedia). For example, one of the risks is jamming or loss of the drill bit due to unknown rock types encountered during drilling, which is generally beyond the control of drillers and drilling engineers. On the other hand, this is also a great need in the mining industry to reduce the exploration costs.

To improve the overall efficiency and reduce the risk of drilling failures, geophysical monitoring methods have been continuously developed in the drilling industry, such as in predicting or evaluating the rock properties around the bore hole to steer the drill bit into expected formations. Measurement-While-Drilling (MWD) is a commonly used technique in oil and gas industry, which acquires real-time geophysical data, such as gamma, electro-magnetic and acoustic, to obtain near-borehole rock attributes and geological structure. However, these measurements are only generally valid in the immediate vicinity of the drill hole. To obtain a large area geological...
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structure around the borehole setting, Vertical Seismic Profiling (VSP) is a conventional borehole seismic method for such a purpose (Hardage, 1985). It is an active seismic method and can be used to obtain seismic velocity and reflection sections around the borehole, but this method requires receiver array to be placed in the borehole, so can only be used after the borehole completion.

An idea to implement a seismic method of providing the merits of both MWD and VSP was studied since 1980s, which led to a new concept of Seismic-While-Drilling (SWD) (Rector, 1990; Rector III and Marion, 1991; Miranda et al., 1996; Naville et al., 2004; Poletto and Miranda, 2004; Poletto et al., 2004). It is a passive seismic method of using the drill-bit noise as vibration source, so there is no interference to the drilling process and no need for an active seismic source. Consequently it is a low cost geophysical monitoring method. Unlike MWD methods that obtain only the local measurements around bore hole, SWD promises to provide geological information about the greater volume around the bore hole during drilling. This is achieved by utilising the drill-bit vibration as a seismic source and a receiver array at the surface or inside a borehole to obtain a record similar to Reverse Vertical Seismic Profile (RVSP), which uses seismic sources in a borehole and receivers on the Earth’s surface (Krasovec, 2001). In an ideal situation, the processing of the drill-bit seismic record can produce a seismic image around the bore hole and ahead of the drill bit. These images can help the drilling engineers and geophysicists to obtain updated geological information to improve the precision of geo-steering.

The successful experiments of SWD were conducted mostly in 1980s and 1990s with a roller-cone bit in favourable conditions. However, the progress of research in SWD has been slow, and the principle reason for the lack of recent progress is due to the conversion to Poly-Diamond-Composite (PDC) bits in the petroleum industry. PDC bits cut the rock using a scraping action rather than by vertical impacts of chisel teeth, as occurs with a roller-cone bit (Hardage, 2009a). Therefore, the wavefields generated by a PDC drill bit are relatively weak compared to the conventional tri-cone drill bit. Consequently, the reflections of the drill-bit generated seismic wavefields are difficult to detect. In mining industry, the cutting mechanism of a diamond drill bit
is similar to PDC bits, and diamond bits are mainly used for medium to ultra-hard rock drilling. In such a drilling environment, it is possible that a diamond bit in hard rock drilling generates higher vibrations into the formation than that PDC bit does in soft rock drilling.

For the SWD application in hard-rock environments, the potential to obtain the diamond drill-bit signal has not been investigated. The main motivation for this thesis is to fulfil potential requirements for the feasibility study of SWD applications in hard-rock environments. This could be particularly significant for Australian mining industry. The detectability of the diamond drill-bit’s direct wave is first step to understand its wavefield characteristics. Also this direct wave from a diamond bit may be used to obtain important local geology information. For example, it can be used to obtain the updated velocity and the time-depth information, eliminating the need for an additional check-shot survey. Furthermore, it can be used to calibrate the surface seismic, resulting in a more accurate migrated seismic image.

1.2 Objectives

The main objective of my research is to investigate feasibility of using a diamond drill bit as a seismic vibration source in hard-rock drilling environments and performing analyses of the SWD signal to obtain geological information around the drilled rock. During my research, there were two diamond drill-bit SWD experiments conducted in hard-rock formations. One was from the Deep Exploration Technology Cooperative Research Centre (DET CRC) drilling site at Brukunga, South Australia. The other was from the Hillside Mine located on the Yorke Peninsula, South Australia.

It is very challenging to deal with the low energy drill-bit signals, particularly in the environments of strong interference noise from the rig site. Specifically, some problems to be understood include dealing with a dominant narrow-band drilling signal, suppressing complicated interference noise from the drill rig and detecting the weak coherent signal in a noisy environment. Most of the investigations focus on the
detection of the drill-bit signal, then use of the signal to perform seismic imaging becomes possible.

The objectives of the thesis can be divided and more specifically stated as:

1. Study the characteristics of the wave field generated by the drill rig and the bit, and investigate different methods to achieve the separation of the drill rig interference noise from the drill-bit signal.

2. Improve the temporal resolution in signal processing of the narrow-band drilling signal.

3. Compare different coherent signal detection methods, focusing on the application of the methods for weak signal detection.

4. Investigate the drill-bit imaging methods, such as interferometric migration by deconvolution.

5. Investigate the drill-bit energy radiation differences between coring using a diamond impregnated bit and Reverse-Circulation drilling method.

1.3 Organisation of the Thesis

The structure of this thesis is organised based on the above objectives. Each one of these objectives is investigated in more detail in a separate chapter. The focus of this research is on detecting the signals of a working diamond drill bit and investigating the diamond drill-bit seismic imaging method. The weakness of the drill-bit signal determines that the investigation of the drill-bit direct wave is necessary and a direct application of the drill-bit direct waves is a velocity analysis based on the drill-bit signal-time delay on a multiple receiver array. For mining industry, successful implementation of this diamond drill-bit seismic imaging method may have important potential in obtaining near real-time information.
Chapter 2 consists of a literature review of SWD development over the last decade, drilling mechanism differences between roller-cone and diamond-impregnated bits, signal crosscorrelation in application to SWD and a brief introduction to coherent signal measurements. For passive seismic methods it is often necessary to use crosscorrelation to compress data and form a shot-gather-like profile for imaging. For a weak drill-bit signal in a complicated noisy drilling environment, I have demonstrated the limitations of standard crosscorrelation using examples from our SWD experiments. The issues are mainly related to recorded dominant narrow-band interference noise from the drilling activity. In such a situation, a higher temporal resolution is required to distinguish different signals. Therefore, to improve the correlation temporal resolution, generalised crosscorrelation as an alternative is reviewed with examples. I showed the different correlation techniques and compare their abilities in handling narrow-band signal correlation. Cross-correlation is also an important technique for interferometry imaging, which is discussed in this thesis for source location imaging.

The results from our first SWD experiment are described in Chapter 3. In this experiment, the SWD data was acquired in a hard-rock formation from Brukunga, South Australia. With diamond-impregnated drilling, this experiment provided us an opportunity to study the drilling signal characteristics. The results of signal analysis from this experimental data indicate the strong drill-rig noise, in which the drill-bit signal can not be visually observed. In this situation, one of the challenges is to overcome the strong drill-rig interference noise to detect the drill-bit signal. In this chapter, a method of using the KL Transform to separate the drill-rig stationary coherent noises is demonstrated in SWD application. This method is studied particularly in emphasising suppressing surface and direct waves from the rig. The usability of the method is demonstrated with synthetic examples. The results show that the method is very effective and appropriate in the application of SWD. The KL transform is compared with \( f-k \) filter to demonstrate its advantages for SWD. Although the KL transform is very effective for handling our field data, even after suppressing the rig wavefield, the drill-bit signal is still not observed in this experiment. At the end of the chapter, I analyse the possible causes for the failure of detecting the drill-bit wavefield.
Signal-detection methods for weak coherent signals are discussed in Chapter 4. I compare a conventional method of semblance with a generalised Multiple Signal Classification (MUSIC) algorithm. The comparison focuses on coherent signal detectability in different situations, such as with timing errors. Spatial resolution is another considerable factor when coherency measurement is used to image a point scatterer. The radiated energy from a diamond drill bit is weak, so one needs to be careful to determine whether the coherent moveout is from the drill bit because there are many noise sources present during drilling. The assessment of velocity of the coherent moveout based on roughly known drill-bit to receiver distances can be used to validate whether the signal is from the drill bit. The success of drill-bit coherent signal detection can be directly used to obtain updated velocity information around the bore hole. We illustrate this velocity-analysis application with synthetic examples and a field data example from a diamond drill-bit SWD experiment at Hillside (South Australia). We show that the diamond drill-bit direct wave can be successfully detected, allowing the formation velocity around the bore hole to be estimated.

The application of drill-bit seismic imaging is further described in Chapter 4. I demonstrate the use of the direct wave interferometry migration algorithm for source location imaging. In order to increase the ability to detect weak drill-bit signals, rather than using a summation method of the migration operator, I suggest integrating the coherent measurement of semblance or MUSIC into the migration operator. I also show the spatial resolution differences of the drill-bit position imaging. I test both methods with synthetic and diamond drill-bit SWD field data. Our field SWD data indicate that the interferometry migration can image the diamond drill bit under appropriate survey settings and the MUSIC method achieves higher spatial resolution.

In Chapter 5, I compare and analyse the seismic signal between core-drilling and RC drilling from the Brukunga experiments. The results show that the two drilling methods produce very different seismic responses. By analysing the signal spectrum and correlation results, RC drilling demonstrates a strong indication of the drill-bit energy. In contrast, the diamond-bit drilling is quieter and therefore it is difficult to conclusively detect a diamond drill-bit signal in the experiment.
1.3. ORGANISATION OF THE THESIS

Chapter 6 summarises the research outcomes and provides the conclusions from the present work and suggestions for possible future work. Finally, the appendix contains an manual of a software package, which was developed during the preliminary stage of my study.
Chapter 2

Literature Review

Abstract

One of the main objectives of this chapter is to review the development history of SWD over the last decade. The conventional drill-bit SWD practice correlates a surface array with a pilot sensor attached to the rig, so as to produce a reverse VSP profile. The success of this approach relies on a good drill-bit signature estimation. When there is not a reliable pilot sensor, a drill-bit interferometry technique is known as an alternative approach to perform drill-bit seismic imaging.

Cross-correlation is the fundamental technique used in drill-bit seismic imaging. In this chapter, signal crosscorrelation examples from our SWD experiments shows the limitations of standard crosscorrelation in drill-bit seismic applications. Study has proved that this is mainly caused by the narrow bandwidth of the signal. To this end, in order to increase the correlation temporal resolution, a generalised crosscorrelation (GCC) techniques are reviewed. I compare and show the differences between different GCC techniques. Additionally, in this chapter, I also review the interferometric migration for source location and reflectivity imaging, which also relies on crosscorrelation to reconstruct a new seismic record. The correlation techniques from this chapter are used throughout the thesis.
2.1 SWD Literature Review

SWD is a passive seismic imaging method. It can also be referred to as the drill-bit seismic method. As stated by its name, it involves the use of a drill bit as a vibration source and its emitted signal to obtain information from around the bore hole. The idea to use a drill bit as a seismic source for investigation of subsurface geological structure was initiated back in 1936. Weatherby (1936) patented such a technique for overburden velocity and bore-hole deviation determination using seismic waves generated by percussive cable drills. Since the 1980s, this idea was being developed rapidly due to growing interests of imaging with Vertical Seismic Profiling (VSP) (Hardage, 1985). Based on the similar concept, Rector (1990) developed the first commercial system of the TOMEX® drill-bit VSP method, which can be implemented while drilling and can remove the need for down-hole source instruments. Figure 2.1 shows the TOMEX® acquisition and processing diagram. The drill-bit generated signal is monitored by a reference sensor attached on the top of the drill string. The pilot signal from the reference sensor is cross-correlated with the surface geophones. This results in a reconstructed wavefield originating from the drill bit to the surface receivers; ideally this would contain the direct and reflected waves. Then a standard migration process is needed to image the subsurface image.

Figure 2.1: Diagram showing a TOMEX® survey (Modified from Rector III and Marion (1991).
Poletto and Miranda (2004) have pioneered many important theoretical and practical studies to implement drill-bit SWD. They investigated the characteristics of the drill-bit seismic waves, drill string waves and noise fields, and also summarised the optimal acquisition and processing methods for the drill-bit SWD data. Poletto et al. (2004) studied a problem of the wave reverberation in the drill string acquired in the pilot signal and suggested to use dual sensors to attach to the drill strings to improve the drill-bit signature record after signal decomposition.

When the drill-bit source wavelet was not known, or there was no reliable reference sensor, Haldorsen et al. (1995) described a method to estimate the source wavelet using an array of surface geophones by extracting and deconvolving a signal generated by a drill bit. Seismic interferometry is another drill-bit seismic method, which has the benefit of achieving imaging without knowing the drill-bit position and wavelet, as described by Schuster et al. (2004) and Yu and Schuster (2006). Vasconcelos and Snieder (2008b) proposed to use a deconvolution interferometry imaging method, when the application of normal crosscorrelation technique could not produce a distinct structured image of the subsurface.

Although there are different approaches to implement drill-bit seismic imaging, the technique has not been adopted as a necessary practice by the industry. One of the main reasons for this is the reliability issue of the drill-bit generated signal due to the change from the rotary cone bit to the PDC bit in the petroleum industry. The quietness of the PDC drill-bit makes it an inadequate vibration source for imaging ahead of the bit. As such there are other seismic survey designs to achieve SWD. For example, the most successful commercial use of seismic-while-drilling is from Schlumberger’s Seismic-Measurement-While-Drilling (SMWD) system. This is not a passive SWD system, as it has the conventional geometry of VSP. SMWD operates a conventional source, such as an air gun, from a rig or a boat. The sensors are deployed at or near the drill bit. The measurements are taken while adding pipe connections and seismic data are processed with down-hole real-time processor. The check-shot data is processed and then sent back to the surface via Measurement-While-Drilling (MWD) telemetry. This technique has been proven in wide range of environments.
2.2. DRILL-BIT ENERGY

By comparison, this approach is very similar to wireline borehole seismic, but there is no need for a wireline cable.

2.2 Drill-bit Energy

The common types of rock drilling techniques include percussive and rotary crushing drilling. Each has vastly different applications, methods and tools (Dennis et al., 1992). The drill-bit type and the related amplitude and frequency of the forces exerted by the working bit, determine the radiation properties (Poletto, 2005). Energy radiating from a working drill bit plays a critical role in determining the suitability in SWD application. The energy emitted from the bit-rock interaction varies largely between different drilling techniques. The Acoustic Emission (AE) is produced from the bit-rock interaction (Ford Brett et al., 1990; Gradl et al., 2008) and is a particularly required energy source for seismic imaging. AE signals are elastic stress waves generated as a result of the rapid release of strain during transformation, plastic deformation and changes in the internal structure of a material (Kovacevic et al., 1998).

There are two types of AE signals originating from deformation based processes: continuous and burst. Continuous type AE signals (Figure 2.2) are lower amplitude, high-frequency signals associated with plastic deformation in ductile materials and erosion processes in brittle materials (Kovacevic et al., 1998). These types of signals do not have any significant resolutions between individual pulses (Everson and Hoessein Cheraghi, 1999). Burst type signals (Figure 2.2) are high amplitude, low frequency signals generated by the spontaneous release of energy during processes such as cracking, trans-granular spalling, fracturing and cavitation (Grosse and Ohtsu, 2008). The burst type of signals is the preferred AE for use in drill-bit SWD according to our experiments, in which the percussion type of drilling produced more favourable signals. The spectrum of the drill-bit signal tends to have a large range, but most of the high frequencies are not usable for seismic analysis.
There are two types of drill-bits used in my experiments: roller-cone and diamond impregnated. The latter one is the main focus of this thesis, but it is necessary to review the roller-cone bit as most of past successful SWD experiments were based on this drill-bit type. Comparisons of the drill-bit’s structures and drilling mechanisms provide a good insight about their energy radiation differences.

### 2.2.1 Roller-Cone Bit

The roller-cone bit breaks the rock by an indentation and gouging action. The force to cut the rock is based on the teeth cutting pressure leading to shear and compressive failure (Adams and Charrier, 1985; Devereux, 1999; Poletto, 2005). A roller-cone bit example from Poletto (2005) is shown in Figure 2.3, where it shows that each cone has two or three rows of teeth. Figure 2.3(a) shows the milled roller-cone bit (non-insert bit), that is used in relatively soft formations at shallow depths (Langenkamp, 1980). Figure 2.3(b) shows the bit has tungsten inserts, which are harder and more durable than milled teeth. The number of teeth in each row of the cone is different. Each tooth is like a chisel and has a maximum height (penetration depth). The cones are supported by bearings, which are lubricated and sealed. The bearing axis of the cone forms the cone journal angle with the horizontal level (Poletto, 2005).
The radiation pattern of a roller cone bit was studied by Rector III and Hardage (1992). One of the results is reproduced and shown in Figure 2.4. As the roller cone bit teeth penetrate, P-waves are radiated along the direction of the axial tooth impact and not perpendicular to the force direction. SV-waves are radiated perpendicular to the impact axis and no SV-waves are radiated along the axis. The SH-wave is the weakest by comparison in the total particle displacement. The vibrations propagating in the axial direction can be detected by placing a sensor such as an accelerometer on the swivel or top drive mechanisms.

The reported successes of SWD are almost all based on roller-cone drill-bit drilling. It is considered to be high-energy seismic source. Two factors contribute to making
CHAPTER 2. LITERATURE REVIEW

Figure 2.4: Roller-cone bit radiation pattern. Reproduced from Rector III and Hardage (1992).

the roller-cone bit a good seismic source: unevenness of the formation and a random breakage process (Poletto, 2005; Ma et al., 1995; Ma and Azar, 1985). Each pulse emitted by a single tooth can be considered as wide-band signal (Hardage, 1992). A laboratory experiment by Gradl et al. (2008) shows that roller-cone bits do not produce any rotationally-related frequency peaks. All of these features make the roller-cone bit a good seismic vibration source.

Poletto (2005) summarised and compared the expected radiation properties of the roller-cone drill bit and conventional VSP sources as functions of key working parameters as shown in Table 2.1. In the table, the drill-bit SWD refers to a roller-cone bit. It shows the roller-cone bit has comparable radiated energy to the vibroseis with 40 min listening time. A more complete table and explanation can be found in the cited paper.

2.2.2 Diamond-Impregnated Bit

Impregnated diamond drilling refers to drilling with bits that contain an arrangement of diamonds in a layer or layers of binding matrices. Two major categories include
2.2. DRILL-BIT ENERGY

<table>
<thead>
<tr>
<th>Source</th>
<th>Drill-bit SWD</th>
<th>Vibroseis</th>
<th>Air gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation</td>
<td>vertical force</td>
<td>vertical force</td>
<td>pressure impulse</td>
</tr>
<tr>
<td>P-waves(^1)</td>
<td>8.8%</td>
<td>6.9%</td>
<td>100% (&lt;100%)</td>
</tr>
<tr>
<td>S-wave(^1)</td>
<td>91.2%</td>
<td>25.8%</td>
<td>0</td>
</tr>
<tr>
<td>Surface wave</td>
<td>0</td>
<td>67.3%</td>
<td>0 (&gt;0)</td>
</tr>
<tr>
<td>Radiation pattern</td>
<td>Lobed</td>
<td>Lobed</td>
<td>Spherical</td>
</tr>
<tr>
<td>Performance specification</td>
<td>(\frac{2\pi rmp \times TOB}{60} + \frac{(ROP \times WOB)}{3600})</td>
<td>peak force</td>
<td>pressure \times volume</td>
</tr>
</tbody>
</table>

\(^1\) Values represent the mean flux of radiated energy and are calculated as a percentage of the total mean flux in the formation assumed as a Poisson’s medium.

Table 2.1: Radiation properties of the roller-cone drill bit and conventional VSP sources. Modified from Poletto (2005).

Impregnated diamond bits and surface set bits. Impregnated diamond bits are used in medium to ultra-hard, deep geological formations, whilst surface-set bits are used in softer formations that are common in shallow drilling (Bullen, 1985).

Figure 2.5: (a) Boart Longyear Impregnated Diamond Bit. (b) Diamond Drill-bit Section. (Boart Longyear, 2009).
Figure 2.5(a) shows a typical diamond drill bit and (b) shows the bit cross section with structure annotation. Impregnated diamond bits are typically 5–30 cm in length, with 0.5–4 cm crown heights and range in core diameters from just a few millimetres to over 100 mm. The body of the bit is usually case steel and includes a threaded attachment mechanism to couple the drilling apparatus. Common impregnated diamond drill bits used in exploration can drill from 80 to 150 m before they are completely worn or fail; however, this is highly dependent on the rock mass being drilled and physical properties of the bit. With deeper exploration, drill-bit life is likely to reduce as harder rock formations are encountered (Boffo et al., 2012). The crown contains many small synthetic diamonds, which are blended into a metal matrix (Akün and Karpuz, 2005). Diamonds are ideal for use in this situation due to their extreme hardness. The metal matrix binding the diamonds is designed to continuously wear during drilling in such a way that unworn diamonds will be exposed, thus providing a continuous renewal of sharp cutting faces (Bullen, 1985).

There are three distinct wear rates in a bit’s life. These include running-in, steady-state and catastrophic/rapid wear (Sudev and H.V., 2008; Baranov et al., 2011), as shown in Figure 2.6(a). The running-in stage occurs in the initial period of drilling when the bit is new. During the running-in period a number of processes are occurring that contribute to a high wear rate. The steady-state of the wear rate occurs when the friction pair reaches a stable equilibrium. Towards the end of the drill-bit’s life the friction characteristics including friction coefficient, wear rate and temperature, increase compared to those in the steady state, shifting the friction equilibrium to favour a faster wear rate. Several frictional processes contribute to this increased wear rate.

Depending on local drilling conditions, the AE profile of this three-stage wear-rate relationship may follow a similar pattern to the wear rate itself as shown in Figure 2.6. For instance, acoustic emissions have high amplitudes in the running-in stage, but these are significantly reduced in the steady-state, then in the wear stage the acoustic amplitude steadily increases with the onset of catastrophic wear (Sudev and H.V., 2008). Therefore, the signals generated from the running-in and rapid wear stages
are favourable for drill-bit seismic, but this contradicts with driller’s preference for steady-state drilling for improved efficiency.

![Diagram of drill-bit wear stages](image)

**Figure 2.6:** (a) Impregnated diamond bit wear stages (Reproduced from Baranov et al. (2011)). (b) Acoustic emission profile of bit life wear rate (Reproduced from Sudev and H.V. (2008)).

AE signals are dependent on the basic deformation mechanisms, such as dislocation motion, grain boundary sliding, twinning and vacancy coalescence, all of which occur during impregnated diamond drilling (Boffo et al., 2012). However, when compared with a roller-cone bit, the continuously radiated energy from a diamond drill-bit while breaking rocks is very low. This state lasts for most of the drill bit life. The
catastrophic wear state provides the highest opportunity for seismic signal detection with this kinds of drill bit.

A rough estimation by Poletto (2005) indicates that the vibration level of the axial PDC forces are typically more than 10 times lower than the vertical forces of roller bit. As the PDC bit drilling mechanism is similar to the diamond impregnated bit, a long listening time is required to capture adequate diamond drill-bit signals.

The application of the passive drill-bit seismic in hard rock environments is one of main subject of the thesis. Since the diamond drill bit is a very weak vibration source, my emphasis is on detecting the direct-arrival drill-bit signal and then using it to derive necessary geological information. Crosscorrelation is a key technique when dealing with passively acquired data. In the following analysis, I review the principle of crosscorrelation and its application to SWD.

2.3 Correlation for Seismic-While-Drilling

2.3.1 Crosscorrelation

For conventional drill-bit SWD processing, a reference sensor at the top of the drill string is used to correlate with a receiver array to generate a Reverse Vertical Seismic Profiling (RVSP) shot gather (Poletto and Miranda, 2004), which can then be further processed using standard processing techniques. Crosscorrelations play an important part in SWD to compress the SWD data and determine the time delays between the reference sensor and surface geophones. Crosscorrelation can be considered as a measurement of the similarity between two waveforms as a function of their relative time delay (Poletto and Miranda, 2004).

The velocity of wave propagation can be estimated from a receiver array by analysing the direct-wave time delay (Garnier and Papanicolaou, 2009). The amplitudes of the crosscorrelation between two receivers contain information about the Green function of the wave equation (Snieder, 2004; Gerstoft et al., 2006; Wapenaar and Fokkema,
2.3. CORRELATION FOR SEISMIC-WHILE-DRILLING

2006; Weaver and Lobkis, 2006), so a proper correlation processing of the receiver signals can be used for geophysical Earth imaging. This is discussed in many papers and forms the basis of seismic interferometry (Wapenaar et al., 2008).

Commonly, the measurements of two real signals at position \(x_a\) and \(x_b\) with discrete time \(t\) can be modelled as:

\[
\begin{align*}
    u(x_a, x_s, t) &= h(t) \ast s(t) + n_1(t)u(x_b, x_s, t) = h(t) \ast [s(t + \Delta t) + n_2(t)] \quad (2.1)
\end{align*}
\]

where \(u(x_a, x_s, t)\) represents measured wavefield at position \(x_a\) for a source at position \(x_s\). \(h(t)\) represents the Earth impulse responses (Green function). \(s(t)\) is the source function. \(\ast\) denotes the convolution. \(\Delta t\) is the relative time delay between receivers at position \(x_a\) and \(x_b\). \(n_1\) and \(n_2\) are uncorrelated random noise.

Then the crosscorrelation coefficients at time delay \(\Delta t\) between two infinite sampled traces can be defined as:

\[
\begin{align*}
    r_{cc}(x_b, x_a, \Delta t) &= u(x_a, x_s, t) \otimes u(x_b, x_s, t) = u(x_a, x_s, -t) \ast u(x_b, x_s, t) \\
    &= \int_{-\infty}^{\infty} u(x_a, t)u(x_b, t + \Delta t)dt \quad (2.2)
\end{align*}
\]

where the symbol \(\otimes\) denotes crosscorrelation. This equation shows the correlation in the time domain is equivalent to convolution for a trace in time-reversed order. For the real-time signals with finite length \(N\), the correlation coefficients at delay time \(\Delta t\) can be expressed explicitly as a dot product of two trace signals.

It is more efficient to compute crosscorrelation in the frequency domain, particularly in the case of a long trace of recorded samples, for example, passive seismic, which usually has the acquired data range from a few minutes to days. It is common and practical to compress the long traces with faster correlation techniques. The Fourier transforms of two real signals at position \(x_a\) and \(x_b\) are

\[
\begin{align*}
    U(x_a, x_s, \omega) &= \int u(x_a, x_s, t)e^{-i\omega t}dt \quad (2.3) \\
    U(x_b, x_s, \omega) &= \int u(x_b, x_s, t)e^{-i\omega t}dt \quad (2.4)
\end{align*}
\]
where $\omega = 2\pi f$ denotes angular frequency, then the crosscorrelation in the frequency domain can be expressed as,

$$R_{cc}(x_b, x_a, \omega) = U^*(x_a, x_s, \omega)U(x_b, x_s, \omega) = |U(x_a, x_s, \omega)||U(x_b, x_s, \omega)|e^{-i\omega(t_b-t_a)} \tag{2.5}$$

where the asterisk symbol denotes the complex conjugate. The absolute value symbol denotes the amplitude spectrum.

This operation of crosscorrelation is equivalent to filtering the signal $u(x_b, x_s, t)$ with signal $u(x_a, x_s, t)$. Therefore, the result of standard correlation will only present the common band energy from both signals.

### 2.3.2 Limitation in SWD Crosscorrelation

With acquired continuous drilling signals in hard rock environments, the limitations of the SWD crosscorrelation are associated with the real signal frequency bandwidth, which is complicated and consists of many narrow-band signals from the drilling related activities, such as the drilling-pattern and strong periodic and quasi-periodic noise from the equipment in the drilling yard, and usually there are strong narrow-band interference noises. For such a complicated signal, the temporal resolution is contaminated by the narrow-band noises when performing standard crosscorrelation. It is likely that the low and weak signal time delay could be masked by the strong narrow-band noise. For example using a 20 Hz single frequency band trace for standard crosscorrelation results in a single-frequency signal as shown in Figure 2.7(a). The true time delay $\tau$ is represented by the largest correlation coefficient, which is indicated by a red arrow. By inspecting the peaks of correlation result, the same period of $2\pi/\omega_0$ with the input signal is shown, but these peaks have similar amplitudes. Figure 2.7(b) shows another correlation result using traces having frequency bands of 20 Hz, 30 Hz and 50 Hz. The true time delay becomes relatively easier to identify in contrast to Figure 2.7(a). This is a well known result that shows the temporal resolution increases with the increase of signal bandwidth. Conventionally,
2.3. CORRELATION FOR SEISMIC-WHILE-DRILLING

Figure 2.7: (a) Signals correlation between two 20 Hz components, (b) Correlation between two traces containing both 20, 30 and 50 Hz signals.

A narrow-band signal is generally defined as a signal whose bandwidth is only a small fraction of the central frequency \( W/\omega_0 \ll 1 \) (Weiss and Weinstein, 1983), where \( W \) is bandwidth and \( \omega_0 \) denotes the central frequency. In the correlation domain, this kind of signal will result in the adjacent peaks having nearly equal amplitude to the maximum coefficient. This limitation of narrow-band signals is commonly observed during standard crosscorrelation in SWD experiments.

Figure 2.8: 0.65 s diamond drill-bit wavelet acquired in laboratory experiment

An experiment to capture the diamond drill-bit signal was carried out in Curtin University laboratory. One of the waveform is shown in Figure 2.8. This signal was acquired with an accelerometer mounted on the side of the rock, while a diamond bit started to drill the rock. The laboratory data was sampled at 5 KHz; then it was
down sampled at 1 ms. The wavelet length is only 0.64 s and its amplitude spectrum is shown on the right panel of Figure 2.8. It shows a strong peak at about 14.8 Hz, which represents the frequency of the drill string rotation. The bit spins at 900 RPM (revolution-per-minute), and is equivalent to about 900 RPM/60 s = 15 Hz. This narrow-band signal is clearly dominant on the spectrum. To study the correlation result with the real drill-bit signal, this wavelet was used to simulate an elastic model as shown in Figure 2.9. In a homogeneous model, the drill-bit source was placed at 1 km underground, using P-wave velocity at 4600 m/s, S-wave velocity at 3000 m/s, and density at 2.5 g/cc. The snapshot of the modelling is shown on the left panel of Figure 2.9. The middle panel is the seismogram; the standard crosscorrelation with a trace on top of the source (2000 m on x-axis) is shown in the right panel. As expected, the correlated shot gather shows strong periodicity due to the narrow-band signal input.

![Figure 2.9:](image1)

A field data example acquired from Brukunga experiment using a diamond impregnated drill bit is shown in Figure 2.10. It shows a two-second pilot raw record (up) and its spectrum (down). The pilot sensor was buried 6 m under the rig. In the time domain, there are similar periodic waveforms observed indicated with the marked circles. The spectrum of the pilot signal is shown at the bottom panel. As seen, there are many strong spikes over the wide bandwidth, which is up to about 450 Hz. Those peaks explain the signal periodicity in the time domain, such as the strong 50 Hz electrical noises and its harmonics, and 60 Hz three-phase diesel generator. The most significant peak around 110 Hz may be harmonics of diesel generator. Similar wide
spectra are also observed in the Poletto and Miranda (2004) SWD experiment. Their analyses results include that shaking and jerks of the hoisting wireline introduce non-linear effects and a broadband ('white') component of surface noise. These types of surface vibrations are recorded in the rig pilot signal and may be transmitted to the formation as surface noise (Poletto and Miranda, 2004). In the situation where the characteristics of the drill-bit spectrum are not known, it is difficult to identify the signals generated by the drill-bit and rock interaction in such a wide-band signal.

Figure 2.10: A two second trace and its spectra from a pilot receiver buried under the diamond-impregnated drilling rig.

Figure 2.11: A two second far-offset trace and its spectra for diamond-impregnated drilling.

Figure 2.11 shows another two second long trace and its spectrum from the Brukunga experiment. Unlike the previous example, this data was not acquired at the rig site,
but from about 100 m further away from the rig. The spectrum demonstrates that
the strong wide-band surface noise may be attenuated quickly. As such, the strong
peaks become more prominent than in the pilot trace.

![Figure 2.12: Standard crosscorrelation of 20s traces between Figure 2.10 and 2.11(Only
1 s correlation causal part shown on upper panel). The lower panel is the spectrum.]

By correlating traces from Figure 2.10 and 2.11 (20 second trace length used), the
result is shown in Figure 2.12. The top panel is the one second causal part of the
standard crosscorrelation. The expected peaks used to identify the signal time delay
are not obvious. In addition, the correlation is heavily contaminated by 110 Hz noises
as shown in the bottom panel spectrum. Although the 110 Hz is not shown as the
strongest band in far offset trace, it is actually the strongest common band of both
traces. As a result, it appears dominant in the correlation domain. Since the 110 Hz
signal is noise, the signal time delay, such as the drill-bit signal, is difficult to identify.
In SWD applications, it is difficult to suppress this type of noise.

2.3.3 Correlation Noises

While there are a number of vibration sources during drilling, most of them are
considered as noise sources, which may include strong electrical and engine noises
as well as other equipment and cultural noises in the rig site. These sources greatly
complicate the detection of the drill-bit signals in the correlation domain. If they are
not identified and suppressed, it is rather difficult for the diamond drill-bit SWD to
be used for seismic imaging.

To study the effects of narrow-bandwidth noise in the correlation domain, two traces
can be modelled for correlation as \( u(x_a) \) and \( u(x_b) \). As shown in Equation 2.1, \( x \)
denotes the position of the received signal. When there is a single source for study,
in frequency domain with included noises they can be modelled as

\[
U(x_a, x_s, \omega) = H(\omega) \cdot S_1(x_s, \omega) + N_1(\omega) \\
U(x_b, x_s, \omega) = H(\omega) \cdot S_2(x_s, \omega) + N_2(\omega)
\]

where \( H(\omega) \) denotes the impulse responses or the Green function and represents the
Earth transfer function. \( S_1(\omega) = S(\omega)e^{-i\omega t_1} \) and \( S_2(\omega) = S(\omega)e^{-i\omega t_2} \) are the delayed
source functions. The only difference between them is the phase shift of \( \omega \Delta t \). The
\( \Delta t \) is the time delay of the source wavelet between traces at \( x_a \) and \( x_b \), \( \Delta t = t_2 - t_1 \). \( N_1(\omega) \)
and \( N_2(\omega) \) are random noises in the frequency domain. Then the crosscorrelation in
the frequency domain between traces can be written as

\[
R_{cc}(x_b, x_a, \omega) = U^{\ast}(x_a, x_s, \omega)U(x_b, x_s, \omega) \\
= (H^{\ast}(\omega) \cdot S_1^{\ast}(x_s, \omega) + N_1^{\ast}(\omega)) \cdot (H(\omega) \cdot S_2(x_s, \omega) + N_2(\omega)) \\
= H^{\ast}(\omega)H(\omega)S_1^{\ast}(x_s, \omega)S_2(x_s, \omega) + H^{\ast}(\omega)S_1^{\ast}(x_s, \omega)N_2(\omega) + \\
H(\omega)S_2(x_s, \omega)N_1^{\ast}(\omega) + N_1^{\ast}(\omega)N_2(\omega),
\]

(2.7)

where the multiplication terms including \( N_1 \) or \( N_2 \) are generally noise, so can be
substituted with a single term as \( R_{nn} \),

\[
R_{nn}(\omega) = H^{\ast}(\omega)S_1^{\ast}(x_s, \omega)N_2(\omega) + H(\omega)S_2(x_s, \omega)N_1^{\ast}(\omega) + N_1^{\ast}(\omega)N_2(\omega),
\]

and the term including both impulse and source functions are signals and can be
denoted as \( R_{ss} \),

\[
R_{ss}(\omega) = H^{\ast}(\omega)H(\omega)S_1^{\ast}(x_s, \omega)S_2(x_s, \omega),
\]

(2.8)

then, the crosscorrelation of the two traces becomes the summation of the above two
terms,  

\[ R_{cc}(\omega) = R_{ss}(\omega) + R_{nn}(\omega). \]

For the signal crosscorrelation term, by reorganising terms and substituting \( S_2, S_1 \) with \( S \) it can be written as  

\[ R_{ss}(\omega) = H^*(\omega)H(\omega)S^*(x_s, \omega)S(x_s, \omega) e^{-i\omega \Delta t} \]  

(2.9)

This equation shows that the signals after crosscorrelation are comprised of auto-correlation of the Earth impulse response, auto-correlation of the source function and a time delay term between the two receivers. Obtaining impulses of the Green function are objectives of seismic imaging.

\[ \text{Figure 2.13:} \quad \text{Auto-correlation of traces from the buried source from Figure 2.9 synthetic model.} \]

As shown in Figure 2.13, the auto-correlation of the ‘pilot’ trace from Figure 2.9 shows a peak at zero time lag. The rest of periodicities lead to low temporal resolution after correlation. However, if one can determine these noises in an auto-correlation domain, a deconvolution filter can be designed to suppress them to some extent.
2.4 Generalised Crosscorrelation

In order to increase the temporal correlation resolution, and suppress the narrow-band noise during correlation, I review the different forms of correlation methods, called Generalised Crosscorrelation (GCC) (Carter, 1987; Knapp and Carter, 1976; Scarbrough et al., 1980). The GCC methods compute the crosscorrelation in the frequency domain, while applying various weighting functions according to required criteria (Miro, 2006). Then, correlation between a trace $u(x_a)$ and a pilot trace $u(x_p)$ can be simply given as

$$G_{cc}(x_a, x_p, \omega) = \Psi(\omega)U^\ast(x_p, x_s, \omega)U(x_a, x_s, \omega) = \Psi(\omega) \cdot R_{cc}$$

(2.10)

Where we use $G_{cc}$ to denote the generalised crosscorrelation. $\Psi(\omega)$ denotes a weighting function, when $\Psi = 1$, the equation is exactly the same as the standard crosscorrelation $R_{cc}$. The use of the $\Psi(\omega)$ weighting function is to whiten the crosscorrelation spectrum, so as to suppress the strong narrow-band noises, such as rig site noise, and improve the resolutions of coherent weak-energy signals, such as the possible drill-bit signal for SWD.

Firstly, I use the inverse of the pilot amplitude spectrum as the weighting function in Equation 2.10, given as

$$\Psi(\omega) = \frac{1}{|U(x_p, \omega)| + \text{stab}},$$

(2.11)

where the general notation for a pilot receiver is $U(x_p, \omega)$ ($x_p$ denotes a reference sensor position). The filter is implemented with so-called water level regularisation applied as a stabilizer, which is shown as the denominator term of $\text{stab} = \varepsilon < |U(x_p, \omega)| >$. When $\varepsilon$ is too small, the deconvolution filter becomes unstable; if it is too large, the denominator becomes constant to simply scale the crosscorrelation. Therefore, the $\varepsilon$ can be determined by visual inspection of the correlation result. The $< |U(x_p, \omega)| >$ represents average of the amplitude spectrum of $U(x_p, \omega)$.

Figure 2.14 shows the auto-correlation result of the pilot channel. It is from the synthetic model of Figure 2.13 after using the weighting function of Equation 2.11.
The resolution of the auto-correlation is improved as the zero-lag peak amplitude is significantly higher from the rest of the periodicity.

Figure 2.14: The filtered auto-correlation of trace from Figure 2.13.

Figure 2.15 shows the comparison of standard crosscorrelation and the spectrum-weighted correlation image using Equation 2.11. The left panel is the standard cross-correlation result, which is the same as shown in Figure 2.9. The right panel is the correlation result after deconvolution with the pilot amplitude spectrum. The correlation result becomes less complicated and the strong direct wave is easier to identify. However, the identification of the S-wave direct arrival is still difficult.

Figure 2.15: Comparison of standard crosscorrelation (Left) and spectra-weighted correlation (Right).

This correlation result can be further improved with the zero-lag spiking Wiener filter, which is equivalent to a least square inverse filter (Yilmaz, 2001). Thus, the
weighting function $\Psi$ can be given as a power amplitude spectrum, which is equivalent to a spiking deconvolution filter. This is also called Roth correlation (Roth, 1971) and is defined as

$$\Psi_{\text{Roth}}(\omega) = \frac{1}{U(x_p, x_s, \omega)U^*(x_p, x_s, \omega) + \text{stab}},$$

where $\text{stab} = \varepsilon < |U(x_p, x_s, \omega)|^2 >$. The weighting function $\Psi(\omega)$ is an inverse of the power spectrum of one input signal in the correlation domain. This filter removes the receiver function of $U(x_p, x_s)$ of the pilot trace. As a result, this operation improves the temporal resolution by spiking the source wavelet in the correlation domain.

**Figure 2.16:** After the Roth weighting function, the auto-correlation of the trace from Figure 2.13 is deconvolved as a zero lag spike.

For the synthetic model of Figure 2.9, Figure 2.16 shows the pilot auto-correlation filter result using the Roth weighting function. Compared with its standard auto-correlation in Figure 2.13, and first deconvolution filtered result in Figure 2.14, the correlation noises from the source function are completely suppressed by the Roth weighting function. It spikes the source function at the zero-time lag. In a linear system, this filter would provide the desired correlation image.

Another method to improve the weak coherent time delay is Smooth Coherent Transform (SCOT) (Carter, 1987; Carter et al., 1973). The weighting function for this generalised crosscorrelation is defined as the inverse of the square root of the amplitude spectrum of both inputs,

$$\Psi_{\text{SCOT}}(\omega) = \frac{1}{\sqrt{U(x_a, \omega)U^*(x_a, x_s, \omega)U(x_b, x_s, \omega)U^*(x_b, \omega) + \text{stab}}}.$$
where the regularisation $stab = \varepsilon < |U(x_a, x_s, \omega)|\cdot |U(x_b, x_s, \omega)|$. So the generalised correlation in the complex coherent form is

$$G_{SCOT}(x_b, x_a, \omega) = \frac{R_{cc}}{|U(x_a, x_s, \omega)| \cdot |U(x_b, x_s, \omega)| + stab}$$

The weighting function $\Psi$ in the frequency domain also whitens the crosscorrelation spectrum by normalising the correlation spectral density. This technique favours both input signals by using their auto-correlation spectra. The SCOT correlation has advantage over Roth correlation when the physical system is not linear. However, SCOT treats the whole band information equally without favouring any particular band signals, which could lead to more complications than the Roth correlation in a noisy system.

In Figure 2.17, I show the comparison of the Roth and SCOT correlation results from the synthetic model of Figure 2.9. Both correlation methods improve the resolution of the wave forms of P- and S-waves with pronounced direct waves, but Roth correlation shows relatively stronger contrast and smoother direct arrivals than the SCOT technique. As seismic imaging is generally treated as a linear system, I will favour the Roth correlation for SWD applications in this thesis. It is noted that there are strong artefacts around time zero for most of the traces after GCC. This is possibly due to the low-frequency stationary phase.

Figure 2.17: Narrow-band GCC Comparison of Roth correlation (Left) and SCOT correlation (Right).
2.4. GENERALISED CROSSCORRELATION

An application based on the coherence function of the SCOT correlation is the magnitude-squared coherence (MSC) (Carter, 1987). It is derived as a function of power spectra of two input signals and their cross-power spectrum, so it is defined by

\[ MSC(x_b, x_a, \omega) = |G_{SCOT}(x_b, x_a, \omega)|^2. \]

Its value lies in the range \(0 \leq MSC(x_b, x_a, \omega) \leq 1\) for all frequencies and this coherent measurement represents the relative linearity of two signals in the frequency domain. When the two single-frequency signals are strongly coherent but time shifted, the MSC value is one. When the value is zero, it means there is no linear relationship at a given frequency.

To obtain the magnitude square coherence, the power spectrum of the smooth coherent transformation is not estimated with a long trace, but using Welch’s method (Welch, 1967) of fast Fourier Transform on a short time window, we then average the estimated outputs. The frequency amplitude in a short window \(w(j), j = 0, ..., L - 1\), with sample numbers of \(L\), can be written as

\[ U_k(\omega) = \frac{1}{L} \sum_{t=0}^{L-1} u_k(j)w(j)e^{-i\omega t}, \]

where angular frequency \(\omega = 2\pi j/L\) and \(k\) is the sequence of windowed segments, then the power spectrum estimate is the average of all segments,

\[ P(\omega) = \frac{1}{K} \sum_{k=1}^{K} |U_k(\omega)|^2. \]

Finally, the MSC of the signal at receiver position \(x_a\) and \(x_b\) obtained in windowed segments can be expressed as

\[ MSC(x_b, x_a, \omega) = \frac{P_{ab}(\omega)}{P_{aa} \cdot P_{bb}}. \]

In the following paragraphs, I apply GCC and MSC on the Brukunga field data. I
use the same signal shown for crosscorrelation from Figure 2.12. Figure 2.18 shows the Roth correlation result. The spectral energy concentrates between 100 Hz and 250 Hz, which is wider than the standard correlation spectrum. As mentioned, this is the result of the spiking deconvolution of the input trace. In this figure, the improved temporal resolution can be seen by three identifiable time delay peaks at about 24 ms, 60 and 144 ms. Therefore, the Roth correlation works effectively, suppressing some low-frequency noises and broadening the spectrum. In Figure 2.19, the correlation is performed with SCOT; the correlation spectrum is flat and broad up to 450 Hz. In the time domain, the three peaks can also be observed. In addition, at 260 ms the peak is not identified from the Roth correlation result. The most coherent peak is at 60 ms, which is different from the Roth correlation result, given its strongest amplitude at the first arrival time of 24 ms. Figure 2.20 shows the MSC coherency measurements for these two traces of Brukunga input data. The most significant peak is at 110 Hz, which corresponds to the strong peak delay at about 60 ms in the time domain after SCOT correlation. In this Brukunga diamond-impregnated drilling experiment, the frequency of 110 Hz is clearly observable. Also there are other peaks, such as 30 Hz, 160 Hz and in the high-frequency band at 270 Hz. These coherent frequency components show relatively smaller peaks in the time domain.

![Figure 2.18](image_url)

**Figure 2.18:** 20 s Roth correlation between pilot and receiver 23 of line 2 (100 m apart) from Brukunga diamond-impregnated drilling experiment.

In summary, the GCC is a technique of applying deconvolution techniques in the
correlation process and is a useful tool for SWD applications. In general, the correlation with a reference pilot channel is a regular practice in SWD (Rector, 1990). The correlation with surface arrays compresses the data and resembles the reverse VSP shot gather; this is based on the pilot sensor approximating the drill-bit vibrations signature with a signal delay. The Roth correlation works effectively to reduce the radiated drill-bit source or other recorded source signatures to a unit impulse. The SCOT correlation and its MSC analysis are good tools to analyse the weak coherent signals and also to determine the significant coherent signal in the frequency domain.
2.5 Optimal Deconvolution

The GCC techniques are closely related to deconvolution. It is well known that by applying a deconvolution filter to a signal, the bandwidth of signal spectrum can be effectively widened, such as Roth and SCOT correlations, but for such deconvolution techniques, a stabiliser (water level regulator) plays a role in controlling the time domain resolution of the deconvolved signal (Chen et al., 2010), which generally needs to be manually tuned. This can be improved with an adaptive weighting function. An optimal deconvolution technique is designed for such purpose (Haldorsen et al., 1994, 1995; Chen et al., 2010). With this technique, the weighting function (a deconvolution filter) is given as,

$$\Psi(\omega) = \frac{U^*(x_p, \omega)}{E_T(\omega)},$$

where $E_T(\omega)$ is average of total energy of the raw traces; $U(x_p, \omega)$ denotes a pilot signal or an estimated source signature.

$$E_T(\omega) = \frac{1}{M} \sum |U(x_m, \omega)|^2.$$

The total energy $E_T$ can be expressed as summation of signal and noise, and then the deconvolution filter can be rewritten as,

$$E_T(\omega) = \frac{1}{M} \sum (|U(x, \omega)|^2 + E(x, \omega)).$$

A semblance weighting function can be placed in frequency domain, so the optimal deconvolution filter equation can have the form of,

$$\Psi(\omega) = \frac{|U^*(x_p, \omega)|^2}{U(\omega)} S(\omega),$$

where $S(\omega)$ is the semblance function and given as,

$$S(\omega) = \frac{|U(x_p, \omega)|^2}{E_T(\omega)}.$$
The factor $1/|U^*(x_p, \omega)|^2$ is the same as Roth correlation (It is also the same as spiking deconvolution factor), but without a stabiliser. Therefore, the final equation describes what one could imagine the implementation of the optimal deconvolution filter as a cascaded filter: a conventional deconvolution followed by semblance weighting (Haldorsen et al., 1994, 1995). The estimated the filter can be treated as a least square optimal for the source signature estimation.

In the case of using a semblance function or to estimate a source signature, a focused receiver array is required. The optimal deconvolution filter designed by this process is proved to be an effective technique for signal processing (Haldorsen et al., 1994). It provides a method to deconvolve noise automatically, and remove the need for a stabiliser.

It is important to explain the use of semblance as a weighting function. Its time domain form is introduced in the later section of this chapter. The result of semblance will limit the signal to the most significant frequency band. The technique has been applied in drill-bit SWD and is proven to be effective, but care is required where applying this method in a situation when there are strong noises. The main reason is because the Haldorsen’s deconvolution method requires estimating the pilot signal with data recorded at the focusing array of receivers. The data needs to be time-shifted, normalised and stacked, so that each observed trace can be assumed to contain a common source signature superposed with a variable noise. This method of estimating source signature requires that one needs to know the moveout to align all the traces. Therefore when dealing with weak drill-bit signal, the identification of the drill-bit moveout might be difficult.
2.6 Seismic Interferometry

2.6.1 Review of Seismic Interferometry

Seismic interferometry estimates the properties of the Earth by analysing the interference patterns of seismic waves (Schuster, 2009). Interferometry imaging is based on the Green function reconstruction from seismic records by crosscorrelating two traces (Snieder, 2004; Schuster, 2009; Wapenaar et al., 2010; Weaver and Lobkis, 2001; Wapenaar et al., 2004; Schuster et al., 2004; Wapenaar and Fokkema, 2006). The concept was pioneered by Claerbout (1968) from auto-correlation; he found that auto-correlation of a trace at the surface is equivalent to the reflection response of an impulse source at the trace position. The later-developed daylight imaging (Schuster, 2001; Schuster et al., 2004) was based on Claerbout’s conjecture: crosscorrelation between trace A and B at the surface is equivalent to a reflection trace at B generated by a source at A. Seismic interferometry has been developed in a number of unique applications. For passive seismic, it is able to turns noise into signal (Hohl and Mateeva, 2006; Garnier and Papanicolaou, 2009; Draganov et al., 2007; Curtis et al., 2006). Another of its applications is to reduce distortion of seismic images by shallow, heterogeneous overburden using the Virtual Source Method (VSM) (Korneev and Bakulin, 2006; Minato et al., 2007; Vasconcelos and Snieder, 2008a).

In an ideal noiseless lossless media, the correlation in frequency domain between two receivers at position $x_a$ and $x_b$ can be given as

$$R_{cc}(x_b, x_a, \omega) = U^*(x_a, x_s, \omega) \cdot U(x_b, x_s, \omega)$$

$$= |S(\omega)|^2 H(\omega) H^*(\omega),$$

where $H(\omega)$ as impulse response is indeed the Green function. For the Green function representation at receiver $x_a$ and $x_b$, the above crosscorrelation equation can be rewritten as

$$R_{cc}(x_b, x_a, \omega) = |S(\omega)|^2 G^*(x_a, \omega) G(x_b, \omega).$$

The symbol $G$ represents both direct and scattered Green’s functions. The Green’s
functions in Equation 2.13 are defined between source \( x_s \) and receivers \((x_a, x_b)\). To implement seismic imaging with interferometry, we need to obtain the Green’s functions between two receivers in 2D/3D situation over a time window length. Equipartitioning is referred to as an important requirement for the successful application of interferometry, which means the waves must be propagating in all directions at each receiver location (Weaver and Lobkis, 2004; Snieder, 2004; Larose et al., 2006). Based on this requirement, integration over multiple sources and over a closed path is performed and is denoted as \( V_{sou} \). This allows us to cancel out the common parts of the Green’s function, which improves the resolution of the impulse responses between receivers. Then the seismic interferometry is generally given as (Vasconcelos and Snieder, 2008a)

\[
\oint_{V_{sou}} R_{cc}(\omega) ds = \langle |S(\omega)|^2 \rangle > [G(x_a, x_b) + G^*(x_b, x_a)],
\]

(2.14)

In here, the integration is interpreted as the wave propagations from all direction at each receiver. However, in an exploration environment this equipartitioning condition is hard to meet. Normally we will have a partial source integration. The lack of primary sources can be compensated by multiples, reflection and scattering in the study region (Vasconcelos and Snieder, 2008a; Wapenaar et al., 2010).

### 2.6.2 Drill-Bit Interferometry

Drill-bit SWD processing is conventionally based on pilot channel crosscorrelation with a receiver array. This topic has been discussed in many papers by Haldorsen et al. (1995); Hardage (2009b); Poletto and Miranda (2004). With the correlation operation, the pilot sensor is assumed to be recording the best approximate signature of the drill-bit vibration. Generally, the pilot sensors are attached to the top of the drill string of the rig; the recorded signal can be expressed as

\[
P(\omega) = T(\omega)S(\omega),
\]

(2.15)
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where $S(\omega)$ is the drill-bit source function and the $T(\omega)$ is the transfer function of the drill string between the drill bit and the pilot sensor. To reduce the pilot signal to an impulse, the deconvolution is usually required as shown in the generalised correlation section. The deconvolution operator can be calculated from the auto-correlation of the pilot (Rector, 1990; Poletto and Miranda, 2004). For the drill string top pilot sensor, the deconvolution operator is

$$F(\omega) = \frac{1}{|T(\omega)S(\omega)|^2}.$$  

The deconvolution operation will remove the drill string transfer function, but it does not remove the reflections in the drill string.

However, in the situations where the drill bit is too far from the rig or in a deviated bore hole, the drill-bit signature may not be recorded properly and the pilot sensor is likely overwhelmingly dominated by the drill-rig noises. For example, this is the observed from our Brukunga diamond drilling experiment described in the thesis. Consequently, the crosscorrelation doesn’t produce the desired RVSP image. In such a case, seismic interferometry provides an optional processing technique, which does not require an independent estimate of the drill-bit source function (Vasconcelos and Snieder, 2008a,b; Wapenaar et al., 2010).

In a passive drill-bit SWD, the signal may be contaminated by strong narrow-band periodic noise, such as the rotation of the drill string or electrical and engine noise. These strong periodic noises will become dominant after the standard seismic interferometry. Vasconcelos and Snieder (2008b) suggested a deconvolution interferometry method,

$$R_D(\omega) = \frac{U^*(x_a, \omega)U(x_b, \omega)}{|U(x_a, \omega)|^2} = \frac{U(x_b, \omega)}{U(x_a, \omega)} = \frac{S(\omega)G(x_b, \omega)}{S(\omega)G(x_a, \omega)} = \frac{G(x_b, \omega)}{G(x_a, \omega)}.$$

This deconvolution process is the same as the previously presented spiking deconvolution, also referred herein as the Roth correlation process. The source signature is independent of processing. As a requirement for interferometry to resemble a new
shot record, Vasconcelos and Snieder (2008b) proposed an intuitive summing process for deconvolution interferometry,

\[ \oint_{V_{\text{source}}} R_D(\omega) ds = \oint_{V_{\text{source}}} G(x_b, \omega) G(x_a, \omega) ds. \]  

(2.17)

Unlike the standard seismic interferometry in which crosscorrelation recovers both causal and anti-causal scattered waves, the deconvolution interferometry only recovers causal scattering responses (Vasconcelos and Snieder, 2008a).

### 2.6.3 Interferometric Migration

Interferometric migration inverts the correlated seismic data for the reflectivity or source distribution (Schuster et al., 2004). One of its applications is for drill-bit seismic imaging.

![Figure 2.21](image)

**Figure 2.21:** Interferometry migration for source location and reflectivity imaging.

Figure 2.21 illustrates interferometry imaging with an unknown source position and its wavelet. It only shows the ray path of direct wave and first and second order multiples. Those events are used for source location and reflection imaging. In the frequency domain, the receivers at position A and B in a homogeneous lossless medium can be modelled as

\[ d_A(\omega) = s(\omega)e^{-i\omega t_{sA}} \]
\[ d_B(\omega) = s(\omega)e^{-i\omega t_{sB}} + s(\omega)Re^{-i\omega(t_{sA}+t_{A}+t_{rB})}, \]  

(2.18)
where \( s(\omega) \) denotes the source signal at position \( s \), \( \omega \) is angular frequency, \( t_{sA} \) and \( t_{sB} \) denote direct waves from \( s \) to \( A \) and \( B \); \( t_{Ar} \) and \( t_{rB} \) are the travel time of first order multiples from \( A \) to \( r \) and \( r \) to \( B \). Then the crosscorrelation between trace \( A \) and \( B \), taking \( d_A(\omega) \) as the reference, is

\[
\Phi(\omega) = d_A^* d_B = |s(\omega)|^2 e^{-i\omega(t_{sB}-t_{sA})} + |s(\omega)|^2 Re e^{-i\omega(t_{Ar}+t_{rB})},
\]

where the asterisk denotes the complex conjugate. Here I ignore some other terms, such as correlation noises. Imaging the underground source position using the direct wave time-delay term in the correlation domain is achieved by summation of the time-delayed response of a receiver array against the pilot channel (Schuster et al., 2004; Yu and Schuster, 2006), namely,

\[
m(x) = \sum_{A,B} \sum_{\omega} \Phi(A, B; \omega) e^{i\omega(t_{xB} - t_{xA})},
\]

where \((A, B)\) denotes the sum over the pair of traces for correlation, \( A \) denotes the reference channel and \( B \) belongs to a receiver array indexed from 1 to \( N \). \( \Phi(x) \) denotes the correlation time delay from \( x \) to \( A \) and \( B \). The kernel of interferometry migration for an unknown source position is the first term of \( e^{i\omega(t_{xB} - t_{xA})} \).

To achieve reflectivity imaging, the migration kernel can be changed to \( e^{i\omega(t_{Ar} - t_{rB})} \). Then the migration is given as (Schuster et al., 2004; Yu and Schuster, 2006)

\[
m(x) = \sum_{A,B} \sum_{\omega} \Phi(A, B; \omega) e^{i\omega(t_{Ar} - t_{rB})}.
\]

The advantages of interferometry imaging are well known, such as no need to know the source wavelet and removing the effect of the distortion surface layer. Its drawback is also demonstrated with Equations 2.20 and 2.21, where the input data contain both direct-wave and ghost reflections. When performing reflection imaging, the direct wave becomes an interference noise source (Yu and Schuster, 2006) and vice versa. A possible solution is to separate the desired wavefields from the others, which is
difficult to achieve. For SWD applications, a technique called the Karhunen-Loéve (KL) Transform is successfully used to suppress the rig noise as discussed in Chapter 3, which, in theory, can also be used to suppress the direct wave.

2.7 Coherency Methods

Coherence is defined as a measure of the similarity among more than two functions (Sheriff, 1973). Coherency measure has important applications for array signal processing / analysis. For example, it can be used in seismic velocity analysis to estimate the travel time parameters, detect continuity/discontinuity events, and determine the signal-to-noise ratio (SNR) (Neidell and Taner, 1971; Shan et al., 1985; Schimmel and Paulssen, 1997). In this thesis, I use coherency measure in the application of weak diamond drill-bit signal detection with a surface multiple-receiver array. Two methods are compared and used in this application. They are semblance and MUSIC. There are detail explanations of both methods in Chapter 4. Herein, a brief description is as follows.

2.7.1 Semblance

Semblance is the normalised output to input energy ratio of a windowed set of traces (Taner and Koehler, 1969; Landa and Keydar, 1998; Yilmaz, 2001), given as

\[ S = \frac{1}{M} \frac{\sum_{x}^{w} \left( \sum_{\tau=-w}^{w} u(x, t(x) + \tau) \right)^{2}}{\sum_{x}^{w} \sum_{\tau=-w}^{w} u(x, t(x) + \tau)^{2}}, \]

where \( M \) is the number of traces indexed by offset \( x \) and time \( \tau \) ranges over a time-window \((-w, +w)\). The semblance has a value in the range \( 0 < S < 1 \).
2.7.2 MUSIC

MUSIC was first developed for angle of arrival (AOA) estimation for narrow-band signals (Schmidt, 1986). This algorithm is able to detect multiple sources. As such, for a multiple-receiver array, the data at receiver $m$ can be modelled as,

$$d_m(t) = \sum_{n=1}^{N} s_n(t)e^{-j\omega \Delta t_m} + n_m(t),$$

where $s_n$ denotes the source function and $n_m$ denotes the noise. As shown in Figure 2.22, the time delay $\Delta t_m$ can be represented by angle $\theta$ and receiver interval $h$. Then a steering vector is given as

$$a(\theta) = \begin{bmatrix} 1, e^{-j\omega \frac{h}{v} \sin\theta}, e^{-j2\omega \frac{h}{v} \sin\theta}, \ldots, e^{-j(M-1)\omega \frac{h}{v} \sin\theta} \end{bmatrix}^T.$$

The steering vector represents the time delays of a recorded wave at each receiver. By utilising the fact that for a perfectly flat event within the analysis window, the steering vector $a$ spans the signal subspace of a data covariance matrix of $d_m(t)$, then the projection of $a$ onto the noise subspace results in a minimum value. As a consequence the MUSIC pseudo-spectrum can be constructed as the inverse of the
2.7. COHERENCY METHODS

projection,

\[ P_{MU}(\theta) = \frac{1}{a^T [P_n] a}, \]

where \( P_n = V_n(\theta) \cdot V_n^T(\theta) \) is the projection matrix onto the noise subspace and \( V_n(\theta) \) represents the noise subspace eigenvectors of the covariance matrix of data \( d_m \). The application of MUSIC for the wide-band seismic signal coherency is discussed in Chapter 4.
Chapter 3

Drill-rig noise suppression using the Karhunen-Loéve Transform for Seismic-While-Drilling Experiment at Brukunga, South Australia

In this chapter, the first SWD experiment is described and the results are present. The experimental data was acquired from Brukunga, South Australia. The drilling was completed with a diamond impregnated coring bit in a hard-rock formation. The characteristics of the drilling signal is studied. This chapter was published in the journal of *Exploration Geophysics*.
Abstract

Diamond-impregnated drill bits are known to be low-energy vibration seismic sources. With the strong interference from the drill rig, it is difficult to obtain the drill-bit wavefield with a surface array. To overcome the challenge of surface wave interference generated from the rig for SWD, we need to separate the rig- and bit-generated signals. To this end, we apply two wavefield separation methods: (1) the KL Transform and (2) the f-k filter, and compare their performance. The applicability of these methods is based on the drill rig and drill bit having different spatial positions. While the drill-bit spatial position changes during the process of drilling, the drill rig remains stationary. This results in the source wavefields from the drill rig and the drill-bit having different characteristics and allows us to separate and extract the drill-bit signal. We use a synthetic model to compare the results from the KL transform and f-k filter methods. Both techniques are robust when the noise wavefield has consistent amplitude moveout. However, for changing amplitudes, such as the rig noise, which has an unrepeatable wavefield due to power amplitude variation, we show that the KL transform performs better in such situations. We also show the results of signal analysis of the SWD experiment data acquired from Brukunga, South Australian. We demonstrate the usability of the KL Transform to separate the drill rig stationary coherent noises in a hard rock drilling environment, particularly emphasising the suppression of the surface and direct waves from the rig. The results show that drill-rig noise can be effectively suppressed in the correlation domain.

Key Words: SWD, KL transform, f-k filter, noise suppression, diamond drill bit

3.1 Introduction

SWD was first proposed and patented by Weatherby (1936) for overburden velocity and drill-hole deviation determination with percussive cable drills. This technique was further developed after the late 1980s’ (Naville et al., 2004; Hardage, 2009b; Poletto
The drill-bit SWD is based on a simple principle, utilising the drill-bit vibrations as a seismic source and a receiver array on the ground surface to produce a Reverse Vertical Seismic Profile (RVSP) seismic record. The coherent noise from the drill rig is not a concern if the drill bit vibration generates adequate signal. However, the lack of recent progress in drill-bit SWD can be attributed to the conversion to PDC bits in the petroleum industry. PDC bits cut the rock by a shearing and grinding action - not by vertical impacts of chisel teeth, as occurs with a rotary-cone bit (Hardage, 2009a). A rough estimation by Poletto (2005) indicates that the vibration level of the axial PDC forces are typically more than 10 times lower than the vertical forces of a roller cone bit.

The basic processing technique for SWD is based on crosscorrelation to generate an active shot-gather-like profile. This relies on measurements of a pilot channel to estimate the drill-bit signature, such as a roller-cone bit. The pilot channel sensor used for crosscorrelation is usually fixed to the top of the drill string, and it measures the drill-bit vibration through the drill string. A good drill-bit signature is not regularly obtained even with roller-cone bits (Anchliya 2006), because of the increasing distance between the pilot sensor and the bit while drilling. Haldorsen et al. (1995) proposed to use the focusing capability of a large receiver array to obtain the drill-bit signature. He also pointed out that the well head is the main noise source, and that by stacking 5 hours of data they could improve the SNR. Another approach of using drill-bit seismic wavefield demonstrated by Vasconcelos and Snieder (2008b) uses a method based on interferometry by deconvolution. This approach has the advantage that it does not need to know the drill-bit wavelet, but it is more restrictive in the setting of acquisition geometry to ensure that the drill-bit wavefield illuminates the imaging area.

A successful implementation of SWD can be used to obtain overburden velocity and yield updated time-depth information while drilling. By imaging the subsurface around the well, it can enable drillers to make informed near-real-time decisions to overcome drilling-related problems, such as sticking and loss of drill strings, improve
drilling safety and overall efficiency. Additionally, the velocity information obtained from SWD can be used to calibrate surface seismic images (similar to real-time sonic logs) (Rector III, 1993).

In hard-rock drilling, diamond coring is a common technique to retrieve intact rock specimens. Its cutting action of a diamond drill-bit is similar to a PDC bit, therefore it’s also a poor seismic vibration source. The drilling depth in hard rock environment, however, is usually shallow (the depths of boreholes are generally less than 1000 m). To extract the useful drill-bit signals, overcoming the strong drill-rig noise interference is one of the main challenges for hard-rock SWD, particularly for the low seismic energy emission from a diamond drill-bit. The suppression of drill-rig background noise has not specifically been studied in previous work. This is possibly because the type of roller-cone drill bit used generates adequate energy (Poletto, 2005). In this paper, we use a mathematical approach, based on the drill-bit and drill-rig space-time difference to suppress the coherent noise. During the process of drilling, the drill bit cuts the rock, and advances deeper, but the drill rig’s position remains stationary. This results in different kinematic characteristics of the source wavefield from the drill rig and the drill bit. We apply wavefield separation in the receiver gather domain and use the KL transform to suppress the rig interference noise to improve the SNR of the drill-bit signal. By comparing this technique with a conventional 2D filter, such as the f-k filter, we claim that this is a more effective method to be used for SWD processing.

The KL transform can be used for coherent noise suppression in seismic processing. For example, Jones and Levy (1987) used the KL transform to isolate coherent components, and suppress multiples to enhance the SNR in multi-channel seismic data. Al-Yahya (1991) showed the application of a partial KL transform to suppress random noise by employing a dip restriction or dividing the seismic section into blocks. Montagne and Vasconcelos (2006) proposed to use the KL transform to suppress ground roll in land seismic data. The application of this method can also be used as signal estimator with the first principle component of aligned wave section (Bostock and Rondenay, 1999). The ability of coherent noise suppression makes the KL transform
an effective tool to separate the drill-bit and drill-rig signals as demonstrated in this paper.

In this paper, we use SWD field data from the Brukunga experiment to demonstrate the performance of the KL transform. A synthetic model is used to demonstrate the wavefield separation results by applying KL transform and f-k filter. Lastly, we show the results of rig noise suppression from the field SWD data.

3.2 Experiment and Field Data

A diamond drill-bit SWD experiment was completed at Brukunga, an old mine site in South Australia. The mine site is located 40 km east of Adelaide (shown at the right bottom corner of Figure 3.1), in an area of rolling hills of the eastern Mount Lofty Ranges. A main iron-sulphide mineralisation occurs as three steeply easterly dipping conformable lenses separated by waste beds (Taylor and Cox, 2003). The experimental drilling program was planned with drilling direction perpendicular to the mineralisation. Drilling was completed with the Boart Longyear prototype core drilling rig. The drill-rig location is shown as a red dot at the centre of the right map.

Figure 3.1: Plan view of receiver lines at Brukunga, and drilling direction. Line 1 is approximately U-shaped. Line 2 is the long SW-NE line. Left Figure shows geophone positions and line numbers. Right Figure shows receiver array overlaid on a Google Earth map. The black arrow indicates the drilling direction originating from the rig (red dot).
3.2. EXPERIMENT AND FIELD DATA

in Figure 3.1, where the bore hole is dipping at 60 degrees towards the west, (the black arrow indicates the drilling direction). The rod rotation speed ranges normally between 600 – 800 RPM. The borehole was completed at a final depth of 324 m. Most of the SWD data was acquired from drill bit depths between 150 m to 190 m. The geophone array layout was limited by the difficult topography at the site. Two seismic lines were deployed on relatively consolidated flat roads. The Line 1 (shown in Figure 3.1 with line number from 1001 to 1084) consisted of 84 channels and was located near and around the drill rig. There was one set of 3-component geophones on Line 1 buried 6 m under the drill rig, acting as the pilot sensor. Line 2 (shown in Figure 3.1 with line number from 2001 to 2096) consisted of 90 geophones along the access road. The geophone spacing was 5 m, and 1 ms time sampling rate was used for the acquisition.

3.2.1 Raw field data

Figure 3.2: Example of 0.5 s raw data from Line 2 (red line on inset map indicates receivers). x-axis is offset from the rig.

Figure 3.2 shows 0.5 s of 90-trace raw data from line 2, with the x-axis indicating the
distance from the geophone to the rig. The traces from the geophones closer to the rig show higher amplitudes than the traces further from the rig. This is the direct result of the strong interference noise from the rig.

![Selected Receivers](image)

(a) Selected Receivers

![No Drilling](image)

(b) No Drilling

![Drilling](image)

(c) Drilling

**Figure 3.3:** Amplitude spectra (log scale) from 2s of data. Each channel is plotted with different colors, marked with increasing relative distance from the pilot (blue channel, buried under the rig). The corresponding receiver positions used for the amplitude spectra are shown in (a).

To show the drilling energy band, the amplitude spectra of selected traces are presented in Figure 3.3, as amplitude spectra of seven 2s long records. The selected receivers are shown in Figure 3.3(a). They are not located from one line and not equally spaced receivers. The zero-offset trace is from the pilot sensor (blue) buried under the rig, and the 19 m offset trace is from the geophone located near the drill pad.
3.2. EXPERIMENT AND FIELD DATA

The 55 m offset trace is also from line 1, but close to the intersection of both lines. The rest of the traces are from the south-west of the lower part of line 2 shown in Figure 3.1. All traces show wide-band spectra, particularly from the pilot and other geophones inside of the drilling yard, which likely indicate multiple vibration sources. The spectra also show that the energy of the traces from the drilling yard (e.g., 19 m offset trace spectrum in green) is about 100 times higher than far-offset traces. When drilling is not engaged (Figure 3.3 (b)), the pilot shows much lower energy compared to others at the surface of the drilling yard, but during drilling (Figure 3.3 (c)), the spectra of the pilot and the receivers at the yard surface become very similar. This means that the pilot signal is strongly contaminated by the rig noise while drilling. The extra energy recorded from the drill-bit is very small. For the far-offset traces, their spectra show a consistent high-energy band from 250 Hz to 450 Hz. These high-frequency bands show little changes between drilling and no-drilling. Also, they don’t change much with different distance receivers, as such this might be the system noise. Overall, except for the pilot trace, the spectra from other traces suggest that there is only a small difference between drilling and no-drilling. This result may be explained by the receivers being close to the rig sites, as such the recorded SWD data are dominated by the drill-rig related coherent noise rather than energy from the bit. This can also be explained as a result of the low diamond drill-bit radiation energy.

3.2.2 Crosscorrelation

Crosscorrelation is usually used to compress the passive data record and construct a shot gather (Weaver and Lobkis, 2001; Wapenaar et al., 2004; Schuster et al., 2004; Wapenaar and Fokkema, 2006; Garnier and Papanicolaou, 2009). To overcome the strong, narrow-band interference noise, and increase the temporal resolution of crosscorrelation, we use the Roth method (Roth, 1971), which uses a deconvolution filter in the correlation domain. The correlation can be conveniently expressed in the
frequency domain as,

\[ \Phi(\omega) = \frac{d_A(\omega)d_B(\omega)}{|d_A(\omega)|^2} = \frac{d_B(\omega)}{d_A(\omega)}, \]

(3.1)

where the asterisk denotes complex conjugation. By deconvolving with reference trace \( d_A \), in an ideal lossless medium, the source wavelet is removed, so the resolution of the time delay increases. Equivalently, the normalisation process widens the correlation spectrum.

Figure 3.4 (a) shows the Roth correlation between Line 1 and the buried pilot sensor under the drill pad. A 100 s window of data is used, and the correlation traces are from the long and straight part of Line 1, as shown on the inset map in red. The result shows strong coherent moveout originating from the rig as indicated by the offset from the rig on the x-axis (The rig is not in-line with the receiver array, so the offset labels are irregular.). Those coherent features include both low- and some high-frequency energy. Figure 3.4 (b) shows the correlation result between part of Line 2 and the buried pilot sensor. The data used for correlation is that shown in Figure 3.2. It also shows a coherent moveout mostly originating from the rig. The other noticeable feature is that the traces on the right-hand side are dominated by low-frequency energy, and high-frequency dominates on the left hand side traces. This may imply different attenuation factors of the rock properties in the region.

By comparison, Figure 3.5 shows standard crosscorrelation results with the same data input as Figure 3.4. The standard correlation works as a band-pass filter. As a result, the weak coherent signal may be filtered and the strong narrow-band signal becomes even stronger in the correlation domain. This results in no distinct direct arrivals being observed as shown in Figure 3.5.

The rig-site produces strong coherent noise in our experiment. These noises are primarily due to random human activities and the drilling process, including vehicle and equipment movement, rig power engines, generators and mud-pump engines. The human or equipment movements are rather complicated in location and timing. To minimise the impact of these noises, it is common practice to use longer records for correlation. In contrast, the rig-power engine, generator and mud-pump are located
3.2. EXPERIMENT AND FIELD DATA

Figure 3.4: Example of 100 s data correlation with the pilot channel from Brukunga, x-axis marked as offset from the rig. (a) Part of Line 1 traces (straight and longer part as shown on inset map in red). (b) Part of Line 2 traces (same data as shown in Figure 2).

in fixed positions, and generate stationary noise wavefields (Poletto and Miranda, 2004). By treating them as a single source with complicated vibration functions, we can simplify the study of drilling vibrations into only two active sources, the drill
bit and the drill rig. As shown in the above signal analysis, the high-amplitude rig-site coherent noise is dominant in the drilling records, so we need to suppress these coherent rig noises with array processing in order to detect the weak drill-bit signal.

3.3 Karhuen-Loève (KL) Transform

To extract the drill-bit wavefield from the drilling records based on its kinematic moveout, we propose to use Karhuen-Loève (KL) transform. The KL transform is closely related to Singular-Value-Decomposition (SVD), as shown in following derivation. It optimally decomposes any complicated data set into a finite, and often small number of modes that are called proper orthogonal modes, empirical orthogonal functions, or principal components. These are obtained from the eigenvectors of the data covariance matrix (Montagne and Vasconcelos, 2006). In seismic processing, the KL transform is usually used to suppress coherent noise or as signal estimator in a windowed data section, such as extracting wave source signature in teleseismic body wave (Bostock and Rondenay, 1999). One of the advantages of this technique is that it results in little distortion of other seismic signals.

A multi-channel seismic data set can be represented as an $m \times n$ matrix $D$, where
3.3. KARHUEA-LOÈVE (KL) TRANSFORM

Each column represents a seismic trace. $D$ can be written as,

$$
D = \begin{bmatrix}
D_{11} & D_{12} & \cdots & D_{1n} \\
\vdots & \vdots & \ddots & \vdots \\
D_{m1} & D_{n2} & \cdots & D_{mn}
\end{bmatrix}.
$$

There are different ways to derive the KL transform. Using SVD, the matrix $D$ can be decomposed into

$$
D = U\Sigma V^H,
$$

where superscript $H$ denotes the Hermitian transpose, $U$ consists of left singular vectors $\vec{u}_i$ ($i = 1, 2, \cdots, m$), an $m \times m$ unitary matrix. $\Sigma$ is an $m \times n$ diagonal matrix, and its diagonal elements are the singular values in descending order $\{\sigma_1 \geq \sigma_2 \geq \cdots \sigma_n\}$. $V$ is an $n \times n$ unitary matrix, and it has column singular vectors $\vec{v}_j$ ($j = 1, 2, \cdots, n$). Any column vector $d_i = \{D_{ji}\}_{j=1}^{m}$ can be approximated as a linear combination of the first $r$ eigenvectors $U$ (Kirlin and Done, 1999),

$$
\hat{d}_i = \sum_{k=1}^{r} (U_k U_k^H) d_i,
$$

In this equation, $U_k^H$ is referred as the Karhuen-Loève transform operator acting on vector $d_i$. Since $\sum_{k=1}^{m} U_k U_k^H = I$ is an identity matrix when using the full rank of the original unitary matrix $U$, for $r = m$ vector $d$ is perfectly reconstructed. But if only the first $r < m$ singular vectors are used, then $\hat{d}_i$ is equal to a low rank approximation of $d_i$. The Karhuen-Loève transform of the data matrix $D$ is given as,

$$
\Psi = U^H D.
$$

The original data $D$ can be obtained by the inverse equation. It is given as,

$$
D = U\Psi.
$$

The optimal estimation of matrix $D$ can be obtained by keeping the first $r$ rows of matrix $\Psi$. This is an important KL transform property (Montagne and Vasconcelos, ...
\( \hat{D}_r \) as a low rank approximation of the matrix \( D \) is given as,

\[
\hat{D}_r = U \Psi_r,
\]

In the case of dealing with contaminating coherent noise, such as the drill-rig noise, the optimal estimated matrix \( D \) represents the rig noise as described in the following synthetic example section. So we need to set the first \( r \) rows of matrix \( \Psi \) to zero. Then, we will have the coherent noise suppressed data as,

\[
\hat{D}_{m-r} = U \Psi_{m-r}
\]

The SVD can also produce the same results. The row vector of \( \Psi \) is equivalent to \( \sigma_i v_i^H \). Then, the data can be reconstructed with low rank approximation as,

\[
\hat{D}_r = \sum_{i=1}^{r} \sigma_i u_i v_i^H = U_r \Sigma_r V_r^H.
\]

Similarly, \( \hat{D} \) can also be reconstructed by using the remaining \( m - r \) eigenvectors, then we will have

\[
\hat{D}_{m-r} = \sum_{i=m-r+1}^{m} \sigma_i u_i v_i^H = U_{m-r+1} \Sigma_{m-r+1} V_{m-r+1}^H.
\]

SVD provides an efficient way to compute the KL transform. Using the first \( r \) singular vectors to reconstruct the matrix greatly reduces the dimensionality for data compression. In the application of suppressing coherent rig site noise, the filtering is done by ignoring the first or the first few singular vectors based on the eigenvalue spectrum or by visual inspection of the result.
3.4 Synthetic Example

In this section, I demonstrate the process of using the KL transform to separate coherent signals of SWD data from a synthetic model. And this method is compared to f-k filter to discuss the different performance between the two techniques. We emphasize the application to SWD to separate the drill-rig wavefield.

A P-wave velocity profile is shown in an elastic model of Figure 3.6, which includes gently dipping layers, and an increasing layer velocity with depth. The red triangles denote the position of the modelled drill-bit. There are 30 shot records, at a vertical interval of 100 m. There are 400 receivers modelled at 10 m spacing at the surface. The drill rig is represented as a round dot at the surface. The rig source signal is modelled with the real Brukunga SWD data, which was acquired from the diamond impregnated bit drilling data recorded by a pilot sensor buried under the rig. The drill-bit source signal is modelled with 14 Hz signal to simulate the drilling rotation, plus added white noise, then convolved with an 80 Hz Ricker wavelet. From the Brukunga SWD experiment, the drilling signal band is generally higher than an active seismic source. This is the reason that we chose this higher centre-frequency Ricker wavelet.
Figure 3.7: Modelled raw data example. (a) A shot gather with modelled bit vibration position at depth of 2 km. (b) A receiver gather at 500 m offset from the rig. The x-axis represents the drill-bit depth.

Figure 3.7(a) shows a modelled shot gather with the bit source vibration at depth of 2 km. The bit modelled with such a long-range depth is to ensure the rig and the bit wavefield having a different moveout for demonstration of the method applicability. The strongest coherent moveouts are S-waves from the rig. Figure 3.7(b) shows a receiver gather including data from all 30 drill-bit shots, which is displayed along the x-axis. As the rig position is stationary, its signal moveout appears as strong coherent flat events in the receiver gather. The drill-bit signal moveout, however, is dipping. The angle of dip is determined by the source-receiver geometry. Based on the different characteristics of the drill rig and bit wavefields, we can directly apply the KL transform to separate the wavefields in the receiver gather without extra data conditioning. Another way to apply the KL filter is in the shot-gather domain, such as in Figure 3.7(a), where one needs to flatten the rig signal moveout, then restore the image after KL filtering. Since flattening of passive drilling data is generally difficult, as well as the KL filter being sensitive to the flatness of the data, this application is less effective than working in the receiver domain. As the coherent moveouts from the rig and bit having different velocity, the wavefield separation can also be done in the f-k domain. We show the comparison between KL transform and f-k filter in the
3.4. SYNTHETIC EXAMPLE

Although in Figure 3.7(b) the receiver gather of raw data shows a coherent flat move-out, the receiver gathers of field drilling data will not display this feature, because there is no time zero for each record of the raw field SWD data. Therefore, this requires us to apply the KL transform in the correlation domain. The correlating with a fixed pilot channel re-aligns source wavefields. In this model, the sensor near the modelled rig is dominated by the rig noise, so we choose trace 111 as the pilot sensor, which is located at 100 m on the right side of the modelled rig source position.

3.4.1 Comparison between the KL transform and f-k filter

While using KL transform for a receiver gather of channel 150, Figure 3.8 shows an example of the diagonal of the $\Sigma$ matrix from Equation 3.2 after correlation with the pilot sensor. The first singular value is significantly larger than the rest, and represents the strong energy of the coherent flat events. So, using the first singular vector ($i = 1$) we can reconstruct the drill-rig wavefields and remove them from the data. Figure 3.9(a) shows the receiver gather, which is 500 m away from the rig. The separated drill-bit and rig wavefields are shown in figures 3.9 (b) and (c) respectively after the KL transform. The drill-bit wavefield shows slow moveout and the rig wavefield displays a flat moveout.

Figure 3.10 shows a reconstructed shot gather at station 15 after wavefield separation. The result is obtained from KL transforms of each receiver gather. Figure 3.10(a) shows the standard crosscorrelation result. Although the middle panel shows well-separated drill-bit signal, it still exhibits strong periodicity, making it difficult to identify the direct arrivals. By comparison, in Figure 3.10(b), after Roth correlation, the correlated raw data in the left panel shows good drill-bit direct arrivals, which demonstrate the advantage of Roth correlation for weak coherent signals. Thus the separated drill-bit direct arrivals are relatively easier to identify as shown in the middle panel. Noticeably, the wavefield separation at the apex is not well achieved, possibly due to indistinguishable drill-bit and drill-rig direct-wave moveout in this.
Figure 3.8: Example of the diagonal values of $\Sigma$ matrix from singular value decomposition of Equation 3.2.

Figure 3.9: KL transform on a receiver gather. (a) Raw data standard cross correlation with reference channel. (b) KL transform separated drill-bit signal. (c) Separated rig signal.

region. This also suggests that, like other event separation methods, it is difficult to separate two events if there is a small apparent-velocity difference.

We can also apply a f-k filter to the receiver gather. Using the same receiver gather as shown in Figure 3.9(a), Figure 3.11 shows the f-k filter results. Figure 3.11(a) is
3.4. SYNTHETIC EXAMPLE

Figure 3.10: Reconstructed shot-gather 15 after KL transform on each correlated receiver gather with trace 111. (a) Reconstruction results from standard crosscorrelation. (b) Reconstruction results from Roth correlation. (Left) Raw data crosscorrelation with reference channel. (Middle) KL transform separated drill-bit signal. The direct arrivals are indicated by arrows. (Right) separated rig signal.

The f-k spectrum of Figure 3.9(a). By muting the column indicated by the arrow, the rig coherent moveouts as constant flat events are filtered as shown in Figure 3.11(b). Figure 3.11(c) shows the residuals after filtering. Comparing to the KL transform, the f-k filter is also very effective in achieving a similar quality of wavefield separation.

The repeatability and variability of signal quality from drilling are the main issues of
SWD surveys (Poletto and Miranda, 2004; Poletto, 2005; Poletto et al., 1997). With hard-rock diamond-bit drilling, the drilling power, including the rig noise, varies with time, so the vibration source function can change with time. Therefore, amplitude variation of the drill-rig signal in the receiver gather is common. But the traveltime of the stationary rig site noise to one receiver remains unchanged. Fortunately, the KL transform is able to match the coherent flat moveout amplitude changes of the rig signal in the receiver gather, but the f-k filter cannot. So KL transform can still effectively separate the rig signals in such a situation. The differences between KL and f-k filters are shown in Figure 3.12 and 3.13 for changing rig signal amplitudes model. This is built by randomly changing the rig direct arrival signal amplitudes as shown in Figure 3.12(a). Figure 3.12(b) shows the filtered drill-bit wavefield, which is almost identical to the result of Figure 3.9(b). Figure 3.9(c) shows the residual of the drill rig wavefield. It shows that the varying amplitudes are separated from the original data.

By comparison, Figure 3.13 shows the f-k filter results. Figure 3.13(a) shows the f-k spectra of Figure 3.12(a). Figures 3.13(b) and (c) are filtered drill-bit wavefield
and the residual, respectively. They are obtained by muting the column in the f-k spectrum indicated by an arrow in Figure 3.13. It is clearly shown that the f-k filter is not as robust as the KL transform in this situation, as the varying amplitudes are not well dealt with in the filtering process. The residual is shown as constant flat moveouts, and the drill-bit wavefield is still contaminated with remaining rig interference noise, such as the bottom part of the figure pointed to by an arrow in Figure 3.13(b). Thus, this advantage of KL transform makes it more appropriate for applications to SWD processing. However, this advantage only exists in SWD receiver gathers, where there are different wavefield moveouts between the drill rig and bit signal. By processing in receiver gathers, not only are the direct arrivals suppressed, but also any coda waves from the stationary noise source, as long as they have flat moveout. However, KL transform is sensitive to the flatness of data matrix $D$, therefore, in a shot gather, the application of KL transform becomes difficult due to uncertainty of drill-rig wavefield flattening. An f-k filter may be more appropriate when the rig is in line with receiver array in a shot gather. In our experiment, however, the receiver array is not a straight line, and the rig is not located on any line. Therefore, the apparent velocity of the wave originated from the rig is much higher than the true velocity. Thus, suppressing the rig wavefield by just filtering the low velocity is inadequate.

### 3.5 Field Data Example

In the Brukunga SWD field experiment, we acquired five days of drilling data while the drill-bit penetrated from 145 to 190 m. For each record, the acquisition system kept listening for 10 minutes. We discovered a problem after correlation of the 5 days data: the clock times of the channels were drifting slowly. This is because our recording system is designed for active surveys, but not well suited for passive seismic. During acquisition, the passive data were acquired by continuously listening for as much as 30 minutes. On the hard drive, the data were saved as one-minute packets for each receiver. The issue we encountered was rather complicated. The
Figure 3.12: KL transform of a receiver gather with changing rig signal amplitudes. (a) Raw data crosscorrelation with reference channel. (b) KL transform separated drill-bit signal. (c) Separated rig signal.

clock drifted continuously for the recording period, such as 30 minutes, for a single receiver. As the recorded data are passive noise, the data is drifted differently from minute to minute, for example, the drift correction for third minute of data might be different from the 20th second data. There are only two channels that have relatively reliable records, but they are both from one line. Corrections to all receivers on other lines are difficult. As such, although we have two lines of 180 geophones, most of the channels have the drifting problems and are unable to be easily fixed. The two relatively stable receivers are trace 46 and 83 and their positions are marked in Figure 3.14(a). They are located on Line 1, opposite the drilling direction. By using them to crosscorrelate with the buried pilot sensor under the drill pad, the receivers gather of five days of correlation are shown in Figure 3.14. Figure 3.14(b) shows the gather of receiver 46, which is buried 5 m underground. It lies in the lower part in Figure 3.14(a), indicated by an arrow. Figure 3.14(c) shows a record of surface receiver 83, which is located at the end of Line 1, and is further from the rig than channel 46. The signal characteristics from each receiver are very different. The signal from buried
receiver 46 seems to be low frequency when compared to surface receiver 83. Even for the single receiver 83, the signal seems to ring more after the drill-bit depth at 165 m. As we know the drill bit was closer to receiver 83 during this drilling period (This is observed by plotting the predicted drill-bit moveout curve as shown in following figures), but it is not certain that this is caused by the drill bit passing by. However, both receiver gathers show strong stationary flat features, which are mainly due to the rig site coherent noise. This noise is less complex on channel 46 compared with channel 83; This might be due to it being buried underground, and therefore noise may not all be rig related, but also wind noise or weather related.

Figure 3.15 shows the KL filtered result of trace 46 receiver gather. Figure 3.15(a) is the diagonal of its singular matrix, where the first singular value is significantly larger than the rest. Figure 3.15(b) is a reconstructed receiver gather without the first eigenvector and the Figure 3.15(c) is the separated drill rig wavefield. The low-amplitude columns are expected to correspond to periods of inactivity at the rig. The expected direct wave from the drill bit on the receiver gather is computed based on relative spatial positions of the drill bit, pilot receiver and this receiver, which is
Figure 3.14: Receiver gather of 5-day Roth correlation with the buried pilot receiver (below the drill pad) of Brukunga SWD data. (a) Plan view of two receiver positions. (b) Trace 46 (buried) Roth correlated receiver gather. (c) Trace 83 Roth correlated receiver gather.

plotted as green and yellow lines. Because we don’t fully understand the diamond bit radiation pattern, we plot the predicted P- and S-wave moveout as reference. As shown, the expected drill-bit moveout dipping is very small at receiver 46, as such, we don’t actually expect to separate the drill-bit P-wave. The predicted S-wave direct arrivals show adequate moveout curve for wavefield separation, however, the recorded amount of S-wave energy is not known by using the vertical geophone at those receiver
3.5. **FIELD DATA EXAMPLE**

![Eigenvalue spectrum](image)

**Figure 3.15:** (a) Eigenvalues spectrum of Figure 3.14(b). (b) KL filter of receiver 46 gather, with reconstruction without first eigenvector. (c) Separated drill-rig wavefield. Green and yellow lines represent the expected drill-bit direct wave moveout curve. 3600 m/s P-wave velocity is used. This is average velocity for 200 m depth at the drilling site derived from zero-offset VSP survey. 2000 m/s S-wave velocity moveout curve is used.

positions. In such a difficult case, we remove the first eigenvector to completely filter only the flat events. Figure 3.15(b) shows no obvious match to the expected drill-bit moveout for both P- and S-waves.

Figure 3.16 shows the KL filter of the station 83 receiver gather. In Figures 3.16
Figure 3.16: (a) Eigenvalues spectrum of Fig 3.14(c). (b) KL filter of receiver 83 gather. Reconstruction without first eigenvector. (c) Separated drill-rig wavefield. Green and yellow lines represent the expected drill-bit direct wave moveout curve. 3600 m/s P-wave velocity and 2000 m/s S-wave velocity are used.

(b) and (c), we show the reconstructed data without the first eigenvector, and the separated drill-rig wavefield, respectively. As for Figure 3.15, we plot the expected drill-bit direct wave as green and yellow lines. As we see in this figure, it is dipping slightly upward. This means the drill bit was closer to this receiver during the time of drilling. The filtered results still show no strong indication of the drill-bit signal. This may be due to an insufficient moveout of the drill-bit signal, which makes it
difficult to distinguish from the rig wavefield. The radiation pattern of the drill bit in this experiment is also not considered, but this aspect should be studied in future experiments by using 3-component receivers. As for an anisotropic source, the unknown radiation pattern of the drill bit could lead to non-optimally positioned receivers, and therefore poor signal sampling. All these factors contribute to the outcome of unobserved drill-bit signal. However, the usefulness of KL filter is still demonstrated, removing the coherent flat events in a receiver gather.

### 3.6 Summary and Conclusions

This chapter has shown results of a trial diamond drill-bit Seismic-While-Drilling experiment in a hard-rock environment. To minimise the impact of drill rig noise, we used the KL transform to separate a possible drill-bit wavefield from the strong drill-rig interference noise. We show the results from a synthetic model and real Brukunga SWD field data. The KL transform can successfully suppress the stationary drill-rig noise as shown in Fig 3.9, 3.10, 3.12, and 3.15, 3.16, and we discuss its advantages in comparison to the f-k filter.

With the Brukunga field experiment, the signal analysis of the raw data, their spectra, and the correlations demonstrate that there is strong rig interference noise in a hard-rock drilling environment. This analysis can be used to understand the noise characteristics of the drill-rig vibration. This result also proves the low signal strength of the diamond drill bit. It is very difficult to separate the drill-bit signal with this field data example, because the predicted drill-bit moveout is close to a flat event. However this example can still demonstrate that the rig noises are effectively reduced after the KL transform. In addition, the field data wavefield separation results also confirm that a diamond drill-bit is a very quiet and low energy vibration source. We also showed that a sensor buried under the drill rig is strongly contaminated by rig noise. Since we cannot easily place a sensor near a working drill bit, attaching a sensor to the drill string could prove to be a good option, as done in most previous SWD experiments.
We have used the SWD synthetic model and the field data to demonstrate that the KL transform is an effective method to suppress drill-rig noise for SWD application. As part of possible future work, we would look at deeper and stronger drilling situation to apply the method to. A new experiment at a site with a flat topography and simple geology setting will provide improved data quality during acquisition. This has been considered for further investigation.

3.7 ACKNOWLEDGMENTS

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Chapter 4

A comparison of coherency measurement using Semblance and MUSIC, from Seismic-While-Drilling perspective

Coherency measurement methods are discussed in this Chapter. I compare a conventional method of semblance with a generalised Multiple Signal Classification (MUSIC) algorithm. Applications of the coherency measurements in SWD are presented. This chapter was published in journal of *Geophysics*
Abstract

A diamond drill bit is usually considered to be an inadequate seismic vibration source. To detect and use the weak drill-bit generated seismic wavefields in hard-rock drilling, we compare different coherency measures between a conventional method of semblance and a generalised MUSIC algorithm. The detectability and resolution differences between semblance and MUSIC are demonstrated with synthetic examples. MUSIC coherency has the advantage of higher resolution over semblance measurement when the source wavefronts are accurately predicted. In addition, we apply both methods to detect the coherent moveout of a diamond drill-bit signal from a hard rock SWD experiment at Hillside, South Australia. We use the coherent moveout to estimate the overburden velocity around the borehole. We also perform interferometry migration using the coherency measurements to image the drill-bit position. The analysis shows that the direct waves generated from a diamond drill bit at shallow depths can be successfully detected, allowing drill-bit imaging and the determination of formation velocity around the bore hole.
4.1 INTRODUCTION

Drill-bit SWD utilises bit vibrations as a seismic source. Its data processing is closely related to Vertical Seismic Profile (VSP) surveys. The application and principle of SWD have been discussed in many papers, e.g., Rector (1990); Haldorsen et al. (1995); Mari and Coppens (2003); Naville et al. (2004); Soma et al. (2004); Yokota et al. (2004); Hardage (2009b); Poletto and Miranda (2004). This technique has been actively developed since the late 1980s in petroleum and engineering applications (Anchliya, 2006). The applications of SWD in the mining industry is of growing interest in recent years, for example, one of the benefits is improved separation of ore from overburden by more-accurate blasting facilitated by using this technique (Goyal and King, 2014; Zhou et al., 2015). In addition, the drill-bit signal can be used to characterise the overburden velocity and to implement geo-steering (Lesso Jr and Kashikar, 1996).

Most published successful cases of drill-bit seismic rely on roller-cone or percussion bits with their high amplitude radiated seismic energy. Since the conversion to PDC bits in the petroleum industry, the progress of SWD using this drill-bit as a source is relatively slow. PDC bits cut the rock by a shearing and grinding action and not by vertical impacts of chisel teeth, as occurs with a rotary-cone bit (Hardage, 2009a). A rough estimation by Poletto (2005) indicates that the vibration level of the axial PDC forces are typically more than 10 times lower than the vertical forces of a roller bit. In the mining industry, the use of diamond drill bits is prevalent. Their cutting action is similar to that of PDC bits, and both are considered to be inadequate seismic sources for seismic imaging in soft rock formations (Anchliya, 2006; Hardage, 2009a). However, in hard rock drilling it is understood that a drill-bit requires more energy to drill a volume of rock than that in a soft rock formation (Miller and Ball, 1990), as such it may generate a good signal-to-noise ratio in a hard-rock environment. An example for such a situation is given by Poletto and Miranda (2004) where a PDC bit generated a good signal while drilling dolomite at depths greater than 1000 m. The use of a PDC bit as a seismic source for downhole, short-range, high resolution acoustic investigation has also been discussed (Poletto et al., 1997; Poletto, 2005). A
robust and comparable VSP result was obtained using a downhole pilot sensor when results were compared between roller-cone and PDC bits (Poletto et al., 2014).

In this paper, we present a hard rock SWD experiment to study the usability of the diamond drill bit as a seismic source. Using a surface receiver array, methods for detecting the diamond drill-bit wavefield require coherent signal detection. The most commonly used coherency detection algorithms include crosscorrelation, semblance and eigenstructure based estimations (Sheriff, 1973; Biondi and Kostov, 1989; Kirlin, 1992). The use of an appropriate coherency measure can improve the signal detection, which is important in analysing and interpreting the seismic data. Herein, we compare multichannel coherency measurements using semblance (Taner and Koehler, 1969; Landa and Keydar, 1998; Yilmaz, 2001) and generalised MUltiple SIgnal Classification (MUSIC) (Biondi and Kostov, 1989; Devaney, 2000; Lehman and Devaney, 2003; Aliyazicioglu et al., 2008; Davy et al., 2009; Gelius and Asgedom, 2011). Besides improving the coherent signal detectability, resolution is another coherency measure attribute that needs investigation. By resolution, we mean the spatial resolution of the location of an underground source. By capturing the direct waves of the diamond drill-bit signal, we are able to perform velocity analysis and image the drill-bit position.

Firstly, we review the semblance and generalised MUSIC algorithms for coherency measurements. Using a synthetic model, we compare the signal detectability and resolution differences when imaging a buried source. Both methods are tested for their abilities to deal with coherent noise and wavefront timing errors. Then we show the application of both coherency methods in SWD velocity analysis with a field data example. Without a special pilot sensor, we demonstrate that the diamond drill-bit direct waves can be successfully detected in the presented field experiment. The formation velocity around the bore hole can be estimated, and imaging of the drill-bit position can be implemented.
4.2 Coherency Measure

Locating a drill bit using its seismic wavefield requires searching the multiple channel data in the xt-plane for possible coherent direct drill-bit waves. In a conventional migration scheme, the buried source position can be migrated based on diffraction summation, which sums the amplitudes in the xt-plane along the diffraction curve for the source point in the xz-plane (Yilmaz, 2001). The summation results in a high amplitude in the migration domain when matching the correct coherent hyperbola curves in the xt-plane.

In inhomogeneous media, the underground acoustic source wavefront is circular in space, and its diffraction shape (or emission shape) can be defined through the traveltime trajectory as

\[
    t = \sqrt{t_0^2 + \frac{(x - x_0)^2}{v^2}},
\]

(4.1)

where \(t_0\) is the zero-offset one-way traveltime from the underground source to the receiver at position \(x_0\); and \(x_0\) is the position vertically above the source; and \(x - x_0\) is a receiver offset to the position \(x_0\). The velocity \(v\) is used to compute the traveltime trajectory. The summation in the standard migration scheme can be replaced with coherency to account for weak signal detection (Schimmel and Paulssen, 1997) or velocity macro-model imperfection (Lee et al., 1993).

4.2.1 Semblance

There are several coherency-measurement techniques for seismic processing. Semblance is one of the most commonly used algorithms. To measure the drill-bit coherent direct wavefront, we can use a semblance measure on a finite time window along the diffraction traveltime curve given by the Equation 4.1. The semblance is the normalised output to input energy ratio of the signal along a windowed hyperbola
(Taner and Koehler, 1969; Landa and Keydar, 1998; Yilmaz, 2001), given as

\[
S(x_0, t_0) = \frac{1}{M} \sum_{\tau=-w}^{w} \left( \sum_x u(x, t(x) + \tau) \right)^2 \sum_{\tau=-w}^{w} \sum_x u(x, t(x) + \tau)^2
\]

(4.2)

where \( M \) is the number of traces indexed by \( x \), and \( \tau \) ranges over a time window \((-w, +w)\). The semblance has a value in the range \( 0 < S < 1 \). The advantage of using semblance over simple summation in diffraction imaging is that it takes account of the similarity of the signals in the given time window. The length of the time window controls the trade-off between a reduced resolution in the time domain and low S/N detection (Bona et al., 2013).

Semblance is a robust measurement that can be used as a constraint in many signal processing applications. For example, Haldorsen et al. (1995) demonstrated the use of an optimal deconvolution filter with semblance in the frequency domain as a weighting operator to minimise the average filtered noise. Semblance is also used in MUSIC coherency as an amplitude constraint (Asgedom et al., 2011b; Gelius et al., 2013).

### 4.2.2 MUSIC Coherency Measurement

MUSIC is a high-resolution algorithm classically used for Direction Of Arrival (DOA) estimation and was first proposed by Schmidt (1986) for narrow-band, uncorrelated multiple emitter locations and signal-parameter estimation. The classic MUSIC uses the covariance matrix of a receiver array as input, and is robust with respect to ambient noise. To be able to handle wide-band seismic data and coherent sources, Asgedom (2012) and Gelius et al. (2013) introduced a window-steered version of classical MUSIC integrated into a coherency-migration scheme. By this approach, seismic diffractions associated with point scatterers can be imaged beyond the classical resolution limit. Time reversal MUSIC is another modified version of the classic MUSIC. It is also a high-resolution algorithm to resolve scatterers beyond the conventional diffraction imaging limit (Devaney, 2000; Lehman and Devaney, 2003; Devaney et al.,...
4.2. COHERENCY MEASURE

The main difference from the classic MUSIC is the use of a Multi-Static Response matrix (MSR) as input data, instead of a covariance matrix. It can handle coherent signals from multiple diffractors, but is more sensitive to noise (Gelius and Asgedom, 2011). The application of imaging point scatterers beyond the diffraction limit, such as faults and small scale fractures, has been shown in a series of publications. The application of coherency using MUSIC measurement can also be used to improve the resolution of velocity analysis (Biondi and Kostov, 1989; Kirlin, 1992).

One important consideration of using MUSIC is that the number of features to be resolved must be less than the number of sources and receivers (Devaney et al., 2005; Asgedom et al., 2012; Gelius et al., 2013). In our application of resolving a drill-bit position with a surface multiple-receiver array, this condition is easily fulfilled. The window steered MUSIC algorithm is described as follows.

In the case of a receiver array with \( M \) receivers, the data can be modelled as

\[
d_m(t) = s(t - \Delta t_m) + n_m(t)
\]  

(4.3)

where the modelled data at receiver \( m \) consists of delayed source wavefield \( s \) and random noise \( n \). \( \Delta t_m \) denotes time delay to receiver \( m \).

**Figure 4.1:** A P-wave shot gather of a buried source (1 km underground) model, velocity=5000 m/s. A steered window for coherency is indicated by the blue lines.
In the time domain, a steered time window is used for the coherency measurement, as indicated by the blue lines in Figure 4.1. The steered window is obtained by a time-shift operation, so there is no wavelet stretching. During this process, it is advisable that interpolation in the time domain should be applied. The MUSIC algorithm is closely related to SVD, which has many different applications for seismic processing, such as wavefield separation or noise reduction (Glangeaud and Mari, 1994; Mari and Coppens, 2003). Using SVD, the $W$ samples of time window data $d_m(t_W) = D$ are decomposed into signal and complementary noise subspaces as:

$$D = [U_s \quad U_n] \begin{bmatrix} \Sigma_s & 0 \\ 0 & \Sigma_n \end{bmatrix} \begin{bmatrix} V_s^T \\ V_n^T \end{bmatrix}$$  \hspace{1cm} (4.4)

where $U$, $V$ and $\Sigma$ represent the eigenvector matrices and singular matrix respectively. The $\Sigma_s$ denotes a diagonal matrix with the $R$ largest singular values, which are associated with first $R$ eigenvectors of $U_s$ and $V_s$ (referred as the signal subspace). $\Sigma_n$ denotes the remaining diagonal matrix (corresponding to the noise subspace).

The coherency in the steered finite-window data measures similarity between row vectors of matrix $D$. After SVD, the columns of $U$ can be interpreted as seismic wavelets, and the columns of $V$ give the normalised amplitudes of the wavelets at each trace. The MUSIC algorithm therefore makes use of matrix $V$ to determine the DOA or number of scatterers by projecting a steering vector onto the noise subspace of $V$. Classically, the steering vector used to scan over the space is a function of angle, and is given by,

$$a = [1, e^{-i\omega\Delta t_1}, e^{-i\omega\Delta t_2}, \ldots, e^{-i(M-1)\omega\Delta t_{M-1}}]^T$$

where $\Delta t$ is a function of angle $\theta$. The angle is known as the signal arrival direction to the receiver array (Schmidt, 1986), and $\omega$ is the angular frequency.

In the window-steered MUSIC approach, a fixed steering vector $a = [1, 1, 1, \cdots, 1]^T$ is used (Asgedom et al., 2012; Gelius et al., 2013). For coherent flat events with relatively constant amplitude in the data window, the signal space is spanned by the fixed steering vector $a$. Because of the orthogonality of signal and noise subspaces, projection of $a$ onto the noise subspace yields a minimum. So placing the projection in the denominator results in a sharp peak for such a coherent event. At the imaging
4.3 SYNTHETIC EXAMPLE OF COHERENCY MEASURE

spatial position \((x_0, z_0)\), the measured MUSIC coherency can be constructed as

\[
P_{MU}(x_0, z_0) = \frac{1}{a^T[P_n]a} = \frac{1}{\sum_i \sum_j [P_n]_{i,j}}
\]

where the estimated source position \((x_0, z_0)\) and velocity model \((v)\) are used to estimate the direct arrival of the source wavefield in a time window. \(P_n = V_n \cdot V_n^T\) is the projection matrix onto the noise subspace. This defines the coherency value at imaging position \((x_0, z_0)\), and is referred to as the MUSIC pseudo spectrum.

The differences and relationship between semblance and MUSIC were discussed by Kirlin (1992). Semblance is a normalised energy ratio, and has value between 0 and 1. MUSIC doesn’t have such bounds. The MUSIC value is more arbitrary than semblance. This property might be the main reason why seismic signal analysis of MUSIC type has not been much discussed in recent years (Gelius et al., 2013). Asgedom et al. (2011b) suggest using semblance as a coefficient in the MUSIC pseudo spectrum. In this paper, only Equation 4.5 is used for velocity analysis and imaging, and there is no semblance coefficient used.

4.3 Synthetic Example of Coherency Measure

4.3.1 Comparison In an Ideal Situation

Figure 4.2 shows the coherency-measurement differences between semblance and MUSIC in an ideal situation. Figure 4.2a shows three steered time-windowed data. The wavelet amplitude is constant in the window. The left window shows a flat coherent moveout. Assuming imaging a distant point scatterer, it represents the steered window matching the diffraction wavefront of the scatterer. By dipping the flat moveout by 0.23 ms/trace incrementally for 15 times, the next two windows with dipping events are selected examples of the steered-window results for different assumed scatterer positions. The last window is the final steered data with largest dipping angle.
The second and third windows can be interpreted as the imaging points not matching the true scatterer position.

![Figure 4.2:](a) Steered time windows with gradually dipping event from a perfect flat (left) to a large dipping angle (right), which correspond to slowly decreasing coherency. (b) Semblance (top left corner) and MUSIC (varying signal space dimension \( R \)) coherency measure corresponding to each steered time window of (a) along x-axis.

The measured coherency for different dipping events is shown in Figure 4.2. We show one semblance and seven MUSIC measurements (with varying signal space dimension \( R \)). For each window, the y-axis is normalised coherency between 0 and 1; the x-axis
is the steering dip of the window data with increasing angle as shown in Figure 4.2a. Semblance is shown to be a robust and stable operation, as its coherency decreases gradually with the increase of the event dip. By comparison, the measured coherency using MUSIC decreases much more sharply than the semblance result. Particularly in the case with low signal space dimension, for example, R=1, 3, 5, the MUSIC values drop to negligible after the first wavelet shift. This gives the high resolution of MUSIC measurements. On the other hand, this can also be interpreted to mean that MUSIC is very sensitive to the flatness of the coherent event. By increasing the signal space dimension R, the sensitivity to the perfect flat event can be reduced. For example, the coherency of MUSIC measure decreases more slowly while using R=13 than the rest of the MUSIC measurements. However, without a perfectly flat event in the steered window, the high-resolution advantage of MUSIC will be reduced quickly, especially with large signal space dimension.

### 4.3.2 Comparison With Added Noise

MUSIC’s imaging resolution beyond the diffraction limit by imaging two nearby scatterers has been shown in many papers with synthetic examples, such as Gelius et al. (2013), Asgedom et al. (2011a), Asgedom et al. (2011b). In this section, we demonstrate the imaging resolution differences between conventional and coherent migration using MUSIC and semblance under different types of interference errors. The emphasis is on resolving a point source (buried at 1 km depth, simulating the drill-bit position) with acceptable resolution, therefore only a single buried point source is used in the synthetic model. In order to compare the results from semblance and MUSIC, the imaging results are normalised between zero and one in the following analysis, so they all have comparable colour scale for display. The modelled source is an 80 Hz Ricker wavelet with a half wavelength of 30 m and the medium velocity is 5000 m/s. To show more details of the source position, the imaging is zoomed into a 400 m×400 m area.
Coherency with Added Coherent Noise

Figure 4.3 (a) shows the same seismogram based on Figure 4.1 with added coherent noise. It is shown that the strong coherent noises masks the source signal from the point diffractor. The modelled coherent noise is constructed by matching the amplitude spectra (both temporal and spatial) in a running window, to the signal of Figure 4.1 while using random phase spectra (Alajmi et al., 2013). Hence the coherent noise has the same spectrum as the signal, but the waveform is completely different. This added coherent noise can represent multiple interference sources.

Figure 4.3: (a) Figure 4.1 seismogram with added strong coherent noises. (b) Migration result of seismogram (a) data.

The migration image is noisy as shown in Figure 4.3 (b), where the correct source position is shown with a strong focus in the middle of the section, however an ambiguous peak at position [1.4 km, 0.85 km] has nearly equal amplitude to the true source.

Figure 4.4 shows a comparison of imaging results using semblance and MUSIC. As the coherency is calculated using a time window, different S/N are calculated along the wavefront with different window sizes. We show the migration results using three different time windows. The noise ratio increase with respect to the measurement window size. The upper panel in Figure 4.4 shows imaging with semblance, and the lower one is MUSIC coherent migration, where the signal subspace dimension R is one.
4.3. SYNTHETIC EXAMPLE OF COHERENCY MEASURE

Figure 4.4: Coherent migration comparison (top: semblance. bottom: MUSIC) in the presence of coherent noise with different S/N. The S/N is determined by the coherent window length (To emphasise the ratio of the noise, noise-to-signal ratios (N/S) are shown on the figure). MUSIC and semblance show comparable results. Coherent noise is difficult to suppress, but at high S/N, both methods show reduced ambiguity.

Both methods image the source position correctly, although the images still appear noisy compared to the migration result. The image resolutions from Semblance and MUSIC are similar under the same S/N. In general, coherent noise is difficult to suppress with various imaging methods. However, the coherent migration window length provides additional control compared to standard migration.

Coherency with Timing Errors

The coherency using MUSIC demonstrates high resolution (Figure 4.2) when the event in the coherent time window is flat. However, such a flat and constant amplitude event may not be seen in real data. Instead, timing errors are common in wavefront coherency measurement, which means the true arrivals don’t coincide with the predicted ones. These errors may be caused by an imperfect velocity model, statics errors or complicated overburden on land seismic.
To understand the coherency difference between semblance and MUSIC in the situation of wavefront timing errors, random and zero-mean shifts are introduced to the moveout curves of Figure 4.1. Figure 4.5 shows two different error curves. One is a timing error with standard deviation $\sigma = 2.4$ ms, which is about $1/5$ of the dominant period (red dashed line), the other has a timing error of standard deviation $\sigma = 5.3$ ms, about $1/2$ of the dominant period (black solid line).

Figure 4.6 shows the results of semblance and MUSIC coherent migration. The input data includes $\sigma = 2.4$ ms standard deviation timing errors from Figure 4.5. The comparison is done with different coherent time window lengths as marked along the x-axis. The correct source position can be imaged with either semblance or MUSIC. Semblance shows good focus, particularly with larger time window lengths. MUSIC coherent migration appears noisier than the semblance coherent migration results when only a single eigenvector is used for the signal subspace (middle row), but the source-position peak is sharper. With increasing signal subspace dimension as shown in the lower panel of Figure 4.6, it becomes less noisy, but the focusing resolution is reduced. The MUSIC demonstrates comparable results to semblance in this example.

For larger timing errors of $\sigma = 5.3$ ms from Figure 4.5, neither semblance nor MUSIC with low signal subspace dimension can resolve the source position as shown in Figure
4.3. SYNTHETIC EXAMPLE OF COHERENCY MEASURE

4.7. When increasing the signal subspace dimension to 8 (lower panel), instead of 1 (middle panel), the higher-amplitude focus of the source position can be identified. Although it is less noisy than the above images, its depth resolution is very low. In general, with included time errors, MUSIC has an extra control of signal subspace dimension over semblance, and can successfully image the source when semblance can not.

Figure 4.6: Coherent migration comparison between semblance and MUSIC. Input data is from Figure 4.5 with timing errors of $\sigma = 2.4\, \text{ms}$. Imaging with corresponding time window length as shown. Top: semblance coherent migration. Middle: MUSIC coherent migration using the first eigenvector as signal subspace. Bottom: MUSIC coherent migration with signal space dimension of 3.
4.4 Application to diamond drill-bit SWD

For a spatially-separated two-point source model \((s_1\) and \(s_2\), e.g., rig and drill-bit, as shown in Figure 2.21), in a homogeneous lossless medium, the direct arrivals at receiver positions \(A\) and \(B\) can be modelled in the frequency domain as

\[
d_A(\omega) = s_1(\omega)e^{-i\omega t_{s_1A}} + s_2(\omega)e^{-i\omega t_{s_2A}}d_B(\omega) = s_1(\omega)e^{-i\omega t_{s_1B}} + s_2(\omega)e^{-i\omega t_{s_2B}},
\]

where \(s_i\) denotes the source function, and \(\omega\) is angular frequency, \(t_{s_iA}\) denotes the traveltime of direct waves from the \(i\)’th source position to receiver at \(A\). Our goal is to determine the time delay of the receiver array against a reference channel. Using
\[
d_A(\omega) \text{ as the reference, conjugating } d_A \text{ and multiplying with } d_B, \text{ we have}
\]
\[
\Phi = d_A^* d_B = s_1 s_1^* e^{-i\omega(t_{s_1B} - t_{s_1A})} + s_2 s_2^* e^{-i\omega(t_{s_2B} - t_{s_2A})} + s_1^* s_2 e^{-i\omega(t_{s_2B} - t_{s_1A})},
\]
\[(4.7)\]

Since the drill bit and drill rig are spatially separated, it is expected that the rig and the bit signals will have different moveout on the surface array. To estimate the velocity based on known relative positions from a source to the array, with \(d_A\) as the reference channel, we can scan the coherent moveout with varying velocities, and produce a velocity spectrum for the known source position. As indicated in Equation 4.7, the cross-talk terms complicate the correlation as interference noises, if \(s_1\) and \(s_2\) are correlated. Therefore, incorrect velocity peaks due to the coherent cross-talk moveout may be observed after the velocity scan. A good knowledge of local geology (together with the knowledge of the drill-bit wavefields) can therefore help distinguish this kind of ambiguity. This issue is demonstrated in the Appendix with synthetic examples. In the next section, we apply coherency velocity analysis with diamond drill-bit SWD field data.

**Field Data Result**

The Hillside mine is located on the Yorke Peninsula, South Australia. The core drilling was done with a diamond-impregnated bit. The drilling direction was towards the west, dipping at 53°. We recorded two days of drilling data using three radial lines around the drilling rig. A line of 147 receivers with 2 m geophone spacing was laid above the bore-hole direction. A vertical section showing the receiver line and the borehole positions is shown in Figure 4.8. In Figure 4.8 the horizontal green line indicates the receiver positions; the dipping line is the projected bore-hole trajectory, where the red dot at the end represents the drill bit at measured depth of about 110 m, which is equivalent to vertical depth of about 85 m. The data collected at this position is used for the following analysis.

Geophone 21 from the receiver line is selected as a reference, because it was located...
Figure 4.8: (a) Hillside SWD diamond-impregnated drilling. The red line is the start of receiver array (From Sun et al. (2014b)). (b) Receiver array (at surface) and borehole trajectory (dipping blue line). The red dot denotes the bit position, where the SWD data was recorded. Channel 21 is used as a reference for correlation with the rest of the receiver array as indicated by the receiver array dashed line.

Figure 4.9: (a) 0.5 s Hillside diamond drilling SWD raw data example; (b) Amplitude spectrum of the raw data (a). It is noted that low frequencies are dominant and deteriorate with offsets.
approximately above the expected drill-bit position. The receiver array including trace number from 21 to 90 is used for the following analysis. A 0.5 second raw data record from the line is shown in Figures 4.9 (a). The raw data shows strong low frequencies. Its spectrum in Fig 4.9(b) suggests that most of the energy is concentrated at 14 Hz, which is associated with the drilling rotation rate at about 800 RPM. It is noted that in Figures 4.9 and 4.10, offset zero on the x-axis corresponds to geophone 21, which is about 70 m away from the rig.

In Figure 4.10, we show the crosscorrelation using the Roth method (Roth, 1971) with the reference channel 21, where the dominant frequencies 14 Hz and 97 Hz are filtered with high-pass and notch filters. The correlation is performed with 24 s of raw data as input. The hard-rock diamond drilling is slow, taking about 20 minutes to drill a 6-meter rod. Therefore, the 24 s correlation record can be considered to be recorded at a stationary drill-bit position (110 m measured depth). Stacking of more data was performed, however, there is no obvious improvement, even the weak coherent signal can be weaker. In Figure 4.10(b), the highest amplitude coherent event corresponds to the low-velocity air wave. The other higher apparent velocity coherent features are also observable as indicated by the arrow. Measuring the linear slope of this coherent moveout yield an apparent velocity of about 3000 m/s as shown. This is considered too high for surface wave moveouts generated by the drill-rig. In a simplified model of having only two vibration sources at the drilling site, the rig and the bit, this should be the direct wave from the drill-bit. In Figure 4.10c, we show the filtered correlation seismogram spectrum. In contrast to the raw data spectrum of Figure 4.9(b), the deconvolution operation effectively widens the spectrum.

Figure 4.11 shows the velocity analysis for the Hillside data using both semblance and MUSIC. Assuming that the wave originates from the rig, based on the rig and receiver position, the velocity spectrum (Figure 4.11a) is obtained by scanning the coherent moveout from Figure 4.10(a). Both semblance and MUSIC produce comparable spectra. For example, a sharp peak is shown at 340 m/s for the air wave. The dominant surface wave velocity is also indicated at about 1000 m/s. Figure 4.11b shows the velocity spectrum using 30 Hz high-pass filtered data as input from Figure
Figure 4.10: Crosscorrelation by deconvolution with a reference channel (surface geophone about 70 m from the rig). (a) correlation seismogram; (b) after 30 Hz high pass filter. Arrow is pointing to the drill-bit direct arrival; (c) Amplitude spectrum of correlated seismogram (b).

It indicates that the filter helps reduce low-velocity surface-wave components significantly, but the sharp peak of the air wave still remains. It is also observed that
Figure 4.11: Velocity spectra assuming that the wave originated from the drill rig, scanning the coherent moveout of Figure 4.10 using semblance and MUSIC. (a) Using raw data. (b) Input raw data are 30 Hz high-pass filtered.

there is a wide-band of high velocity around 3000 m/s, which is probably aliased energy from other sources, for example, the drill bit, while in this spectrum the velocity scanning considers the rig as the only vibration source. A synthetic model demonstrating such aliased energy is shown in Figure 4.17 in the Appendix of the chapter.

Figure 4.12: Velocity spectra by assuming the wave originated from the drill bit, scanning the coherent moveout of Figure 4.10 using semblance and MUSIC. (a) using raw data. (b) 30 Hz high pass filtered raw data

Figure 4.12 shows the velocity analysis assuming that the seismic wave originated from the estimated drill-bit position (the vertical depth is about 85 m). Using the same correlation seismogram of Figure 4.10 as inputs, Figure 4.12a shows the velocity spectrum from scanning the original correlation data; Figure 4.12b is the velocity
spectrum using 30 Hz high-pass filtered correlation data as input. The spectra both show peak velocity components between 1300 m/s and 1500 m/s. Based on the spatial positions of rig, bit and receivers, the estimated velocity from the drill-bit direct wave moveout will appear to be twice as fast if the moveout is assumed to originate from the rig. Hence, comparing the different velocity spectra, the 1500 m/s peak in Figure 4.12 is aliased at wide-band around 3000 m/s shown in Figure 4.11. This matches the above velocity analysis results. Therefore, this sharp peak in Figure 4.12 indicates the possible overburden velocity between the drill-bit and the receivers.

To verify the velocity estimation result, we show the Hillside P-wave velocity section from a nearby refraction survey in Figure 4.13. The shallowest 40 m of the site has a low velocity profile, particularly on the eastern side of the line. The SWD site is located 600 m further east of this profile. Additional confirmation comes from processing of a local active seismic survey, where the Root-Mean-Square (RMS) velocity for the first 100 m was about 1800 m/s. Thus both the refraction and shallow reflection velocities broadly agree with the velocity estimated from the SWD data.
4.4.1 Diamond drill-bit imaging

Drill-bit interferometry method

Using the detected drill-bit coherent signal and estimated overburden velocity, imaging the drill-bit position is possible. Interferometry migration is a well-known technique for passive seismic imaging. Herein, we integrate the coherent measurements into the migration process and compare the imaging results.

Interferometry migration relies on crosscorrelation to reconstruct a seismic record analogous to an active shot gather (Weaver and Lobkis, 2001; Wapenaar et al., 2004; Schuster et al., 2004; Wapenaar and Fokkema, 2006). It inverts the correlated seismic data for the reflectivity or source distribution (Schuster et al., 2004). A known source vibration signature can improve correlation results while applying interferometry migration. One method to estimate the drill-bit signature is to use a receiver array (Haldorsen et al., 1994; Stewart Taylor and Coates, 2007), for example in a situation that the drill-bit is far from noise sources, such as the drill rig, but the receiver array is deployed near the drill bit. However, in our drill-bit SWD experiment, the diamond drill bit is a weak seismic source; and the drilling depth is shallow, so additional strong interference noises from the rig cannot be minimised from survey planning. Thus, the estimation of the drill-bit signature becomes difficult. We focus on the application of source position imaging using its direct arrivals.

The drilling signals are usually dominated by narrow-band noise, such as noise from drilling rod rotation as shown in Figure 4.9(b). With standard crosscorrelation, these noises complicate and mask the desired weak signal. To widen the crosscorrelation spectrum and improve detectability of the weak signal, deconvolution interferometry migration is utilised. This result is shown in Figure 4.10c. The deconvolution can be conveniently expressed as (Vasconcelos and Snieder, 2008a),

\[
D(\omega) = \frac{d_A(\omega)d_B(\omega)}{|d_A(\omega)|^2} = \frac{d_B(\omega)}{d_A(\omega)},
\]

where an asterisk denotes the complex conjugate. By deconvolving with the reference
trace $d_A$, this operation removes the receiver function $d_A$, widens the cross-spectrum, and improves the temporal resolution.

Based on the illustration of interferometry imaging for an unknown source distribution in Figure 2.21, an image can be obtained using the direct wave term in the correlation domain. By using summation of time-delayed responses of a receiver array against the reference channel (Schuster et al., 2004; Yu and Schuster, 2006), the direct wave interferometry can be expressed as,

$$m(x) = \sum_{A,B} \sum_{\omega} D(x; A, B; \omega)e^{i\omega(t_x B - t_x A)}, \quad (4.9)$$

where $D$ is the correlation by deconvolution shown in equation 4.8. $A$ and $B$ denote traces for deconvolution. $x$ is the migration spatial position. The kernel of interferometry migration for the unknown source distribution is the factor $e^{i\omega(t_x B - t_x A)}$. When migration position $x$ matches the source position $s_2$ (the drill bit), the summation produces a constructive response, and the drill bit can be imaged.

For weak signals the averaging produced by the migration summation may not be sufficient to overcome the strong noise. Instead, the coherency measurement (semblance and MUSIC) can be used in the interferometry migration process. Then the coherent interferometry migration can be expressed as,

$$m(x) = \text{coherency} \left( \sum_{\omega} D(x; A, B; \omega; \tau)e^{i\omega(t_x B - t_x A)} \right), \quad (4.10)$$

where $\tau$ denotes the time window over which coherency is measured.

**Field Data Example**

We use coherent interferometry migration to image the drill bit within a 70 m×70 m vertical section for the Hillside SWD experiment. The same dataset is used as for velocity analysis from Figure 4.10. The velocity spectrum in Figure 4.12 shows that the peak velocity lies between 1300 m/s and 1500 m/s. After comparing the imaging
focus matched to the estimated drill-bit position (marked with blue triangle in Figure 4.14), a constant velocity of 1300 m/s was selected for migration. There is no need to use a layered velocity model for this shallow depth (about 100 m) in the hard-rock environment. A constant effective velocity model is adequate for this short surface receiver array.

Figure 4.14 shows the coherent interferometry migration result with semblance (a) and MUSIC (b). Both coherent migration methods produce comparable images with low spatial resolution in the depth direction. This is due to the limited receiver array aperture as shown in Figure 4.8, only 70 channels (spanning about 140 m) on the west side of the rig are used. This low resolution can be reproduced by synthetic model as shown in Figure 4.18(b) (as seen in the Appendix of this chapter). Also, from the synthetic model in the Appendix, the high resolution advantage of using MUSIC method is demonstrated in Figure 4.18, but for the field data in this section, it is less obvious. From the synthetic data comparison between semblance and MUSIC, it is understood that this is due to poorly conditioned data for coherency measurement in the steered time window.

Figure 4.14: Diamond drill-bit imaging at targeted area with migration velocity of 1300 m/s from Hillside SWD experiment. (a) semblance, (b) MUSIC. The triangles represent the expected drill-bit position
4.5 Discussion

The comparison between semblance and MUSIC focuses on signal detection and resolution improvement for seismic analysis. We have shown that semblance is a robust measure in handling noise and timing error and that MUSIC shows comparable results in the same situations. In addition, MUSIC has one extra parameter (signal space dimension R) to control the output. An appropriate choice of R on well-conditioned data can result in superior performance, however, the choice of R is still not automated, and as such using a default value (say R=1) may not lead to significantly improved results compared with semblance when there are signal / measurement errors. The choice of R is part of an ongoing study. Furthermore, unlike semblance, MUSIC can produce arbitrary output values. This might be the main issue that is preventing MUSIC being commonly applied in seismic analysis. For the cost of computation, MUSIC measurement takes slightly longer than semblance. This is not a big issue for modern computer speeds.

For velocity analysis using coherent method, only direct arrivals to surface receiver array from the rig and the bit are considered, however, velocity of refracted event from the rig should be analysed and it is also a possible result. For future work, a ray tracing method could be used for such analysis. However, regardless that the observed moveout is direct or refracted wave, it is a result that characterises the shallow depth formation.

4.6 Conclusion

In this paper, we compare the use of semblance and MUSIC coherency for improving coherent signal detection, as well as achieving reasonable resolution in imaging a drill-bit seismic source. Semblance is widely used in seismic coherency analysis. The MUSIC coherency, also referred as window-steered MUSIC, has higher spatial resolution compared to semblance. It also shows improved signal detection through the ability to control the signal subspace dimension. With added coherent noise and
large wavefront timing errors, MUSIC coherency is still comparable to semblance. It can image the source position under large time errors which semblance cannot handle as shown in Figure 4.7. In general, when using MUSIC coherency, by increasing the dimension of the signal subspace, one can increase the signal detectability by tolerating less-coherent events at the cost of reduced resolution. MUSIC coherency measurement can serve as a good complement to semblance for potentially improved image details.

An accurate velocity model around the borehole is important for drilling engineers and geophysicists. We demonstrate velocity analysis based on scanning the coherent drill-bit direct wave in the correlation domain. We also implement coherent interferometry migration for drill-bit position imaging. The application of the velocity analysis is demonstrated with diamond-impregnated drill-bit SWD data from Hillside in South Australia. Although a diamond drill bit is a weak seismic source, we are able to detect its direct waves and obtain consistent velocity information from SWD when the depth of drilling is shallow. This velocity broadly agrees with reflection and refraction velocities at a nearby survey. Thus, we expect that this method would be even more successful with other more noisy drilling techniques, such as percussion drilling, and could be used for deeper drilling experiments.

\section{4.7 ACKNOWLEDGEMENTS}

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anonymous reviewers for their insightful comments and thoughtful consideration, which has improved the paper significantly.
Appendix

4.A SWD Synthetic Example for velocity analysis and interferometry migration

Herein, a 2D synthetic model is used to test field-data results in drill-bit velocity analysis and interferometry imaging. In the model Figure A.4.15, there are two vibration sources denoted by the triangles at the ends of the red line, and the blue line at surface denotes the receiver positions with 2 m spacing. To match the Hillside experiment acquisition geometry, we use only the receivers marked in green (right half of the line) for the imaging analyses. The surface source wavelet is modelled with a real data record from Hillside recorded at about 15 m from the drill rig. The buried source wavelet is modelled with 14 Hz spikes to simulate the drilling rotation, plus added white noise, then convolved with an 80 Hz Ricker wavelet (This frequency choice is based on the fact that the diamond drill-bit of this experiment generates signals with high frequency components in the seismic range). Figure A.4.15b and A.4.15c show the modelled data for the receivers in the green segment receiver line and its spectrum, respectively. The spectrum shows a strong energy band around 60–150 Hz.

4.A.1 Velocity Analysis

Using the same velocity analysis method described in the section on SWD Reference Channel Velocity Analysis, Figure 4.16 shows the modelling velocity-analysis results using semblance and MUSIC. Using the same 5-point time window, we plot the estimated velocity spectrum assuming that the wave originates from the rig in Figure
Figure 4.15: A 2D synthetic model is used to test field data results. (a) Multiple-layer velocity model. (b) Modelled raw data for two vibration sources from receivers marked in Green. (c) Amplitude spectra of the raw data of (b).

4.16(a) and from the drill bit in Figure 4.16(b). In either case, the velocity between the sources and receivers is correctly estimated with both semblance and MUSIC. The direct wave from the rig has an estimated velocity of 1000 m/s, and from the bit, 1500 m/s. The MUSIC algorithm shows slightly sharper peaks, particularly when using the bit as the source.

In Figure 4.16 (a), the velocity spectrum is noisier than Figure 4.16 (b). In particular there is higher velocity peak after 5000 m/s. To understand this extra peak, we use synthetic data consisting only of the drill-bit wavefield to perform the same velocity analysis as above (assuming waves originating from the rig and the bit positions). Figure 4.17 shows the velocity spectra, where Figure 4.17 (a) is the result assuming
**Figure 4.16:** Using the green line receiver array, the velocity spectra are obtained based on semblance (black dash line) and MUSIC (red line). (a) Estimation is based on the coherent moveout originating from the rig; (b) from the bit.

**Figure 4.17:** Using just a single drill-bit wavefield, the velocity spectra based on semblance (black dash line) and MUSIC (red line). (a) Estimation is based on the coherent moveout originating from the rig. The 1000 m/s peak disappears due to absence of the drill rig wavefield, but the velocity of the drill-bit direct arrival is incorrectly plotted between 4000 m/s and 5000 m/s; (b) Estimated velocity spectrum based on correct drill-bit position, yielding the correct velocity.

It shows that the low-velocity energy from the drill bit appears as a higher velocity just at below 5000 m/s. The difference from the field data, where the aliased velocity is 3000 m/s, is due to the relative position differences between rig/bit and the receiver array. Figure 4.17 (b) spectrum uses the correct source position for the drill-bit wavefield, and it produces almost an identical result to Figure 4.16 (b). This type of ambiguity is also observed from our field data example in the main text.
4.A.2 Interferometry Migration

With the same synthetic model shown in Figure A.4.15, to image the source, we restrict our imaging to a $160\text{ m} \times 160\text{ m}$ square area, where we expect the drill-bit to be located. Then, we apply coherent interferometry migration to the passive wavefield to that area.

In our Hillside experiment, we have only a single-sided array available for processing, to see the imaging differences between limited and full aperture receiver array, we test this synthetic imaging result using full (blue line) and a single sided (green line) receiver array. Figure 4.18(a) and 4.18(b) show the migration results using semblance, (a) is the imaging result with full array of receivers on both sides of the rig; (b) uses a single-sided array. Figures 4.18(c) and 4.18(d) show the imaging results using MUSIC with signal subspace dimension $R$ as two. The results show correct focus at $[500\text{ m}, 700\text{ m}]$ from Figure 4.18(a) and (c), and relatively higher resolution is observed from MUSIC method. The velocity used for migration was 1400 m/s, which agrees generally with the velocity spectrum in Figure 4.16b. The imaging results show poor resolution over depth, particularly for the case of the one-sided array, which agrees with the field data imaging results. The low vertical resolution is due to the limited aperture, and the migration operator spread over depth (Schuster et al., 2004).
Figure 4.18: Synthetic data coherent interferometry migration for a 160 m × 160 m window 2D vertical section. (a) and (b) Semblance method; (c) and (d) MUSIC method (R=2). (a) and (c) using the full-offset array; (b) and (d) using only the one-sided array.
Chapter 5

A comparison of energy radiation from diamond-impregnated and reverse-circulation drill bit during hard-rock drilling

In this Chapter, I compare and analyse the seismic signal between diamond core drilling and RC drilling from Brukunga experiments. This Chapter was published in journal of *Geophysics*. 
Abstract

We compare and analyse hard-rock drilling elastic energy emission between diamond-impregnated coring and Reverse-Circulation (RC) percussion drilling methods from an experiment at Brukunga, South Australia. The two drilling mechanisms generate very different seismic wavefields. This comparison emphasises their energy radiation differences and signal characteristics. From the field data, by investigating the raw data energy, frequency analysis and crosscorrelation tests, the seismic records from percussive RC drilling provide a strong indication that the drill-bit energy can be suitable for drill-bit seismic imaging purposes; the energy radiation from the percussive RC bit may also provide high-resolution images with borehole seismic acquisition. In contrast, at comparable drilling conditions the coring drilling using a diamond-impregnated coring bit is quiet, the radiated acoustic energy from this drilling mechanism is difficult to detect by a surface receiver array, and there is no visible convincing drill-bit signal observed in the experiment.
5.1 Introduction

Common types of rock drilling include percussive and rotary drilling. Each has very different applications, methods and tools (Dennis et al., 1992). For example, impregnated diamond bits are used in medium to ultra-hard deep geological formations (Bullen, 1985). This type of bit is widely used in the mining industry for core retrieval. The study of a drill bit generated wavefield can be used to support drilling and geophysical exploration. Its applications, such as interpreting lithology using the drill-bit seismic waves, have been extensively discussed by Poletto and Miranda (2004). As such, it is important to understand the difference in bit energy radiation, so as to assist in planning geophysical monitoring.

It is well known that the energy generated by a drill bit varies with its design, wear and drilling parameters, such as RPM, Weight-On-Bit (WOB) and bit-rock interaction (Poletto and Miranda, 2004). These drilling parameter variations are due to a large variety of configurations of mechanical drilling equipment, operational parameters, and geophysical settings (Poletto, 2005). It is common practice that the drilling parameters are chosen on the basis on the driller’s experience in hard-rock drilling. This is the reason that it is difficult to compare different drill-bit radiated energy in a field experiment. In this paper, we compare and analyse elastic energy emissions between diamond-impregnated coring and Reverse-Circulation percussion drilling methods at the same drilling site. As such, similar rocks are drilled in order to provide a direct comparison between the two different drilling methods.

The cutting action of a diamond-impregnated drill bit is similar to a PDC bit, and is very quiet while drilling. A rough estimation by Poletto (2005) indicates that the vibration level of the axial PDC forces are typically more than ten times lower than the those of the vertical forces generated by a roller cone bit. Gradl et al. (2008) analysed the different drill-bit noise characteristics under different rotation rates in laboratory conditions. This experiment shows that diamond drill-bit signal amplitude spectra are wide with distinct peaks related to the rotation speed and the bit cutting structure, and that the roller cone bit’s spectra show significant peaks, which are
independent of rod rotational speed. The roller cone bits are demonstrated as an adequate seismic vibration source for seismic imaging. The energy is expended by teeth indentation and lobe patterns with modulated periodic or random components by the drill string torsional pendulum (Poletto, 2005). Its use for SWD is proven through many previous publications for applications in the petroleum industry or geo-technical engineering (Rector, 1990; Haldorsen et al., 1995; Mari and Coppens, 2003; Naville et al., 2004; Soma et al., 2004; Yokota et al., 2004; Hardage, 2009b; Poletto and Miranda, 2004; Zhou et al., 2015).

The seismic spectrum from a diamond drill-bit drilling may be wider than that from a roller-cone bit, but there are not many successful case studies using this type of bit as a seismic source, because the radiated energy from a diamond bit to the formation is inadequate for seismic purposes (Anchliya, 2006; Hardage, 2009a). This is attributable to its shearing cutting mechanism. For this type of vibration source, the radiated amplitude of the compressional wave is much smaller than the shear amplitude (Tang et al., 1994). In addition, it is also difficult to quantify the vertical and lateral vibration energy (Poletto, 2005). Numerical modelling demonstrated that PDC bits induce large amplitude torsional and axial drill-string vibrations, during transients in the applied weight on the bit and during drilling at a low weight and high rotary speed (Langeveld et al., 1992).

The low radiation energy of PDC bits for seismic analysis has been mostly reported based on soft-rock drilling experiments (Poletto and Miranda, 2004). In hard-rock environments, Poletto and Miranda (2004) demonstrated a good PDC-bit generated signal while drilling dolomite at depth of 1300 m to 1350 m. This provides us with the motivation to study diamond SWD. In hard-rock core drilling, the diamond-impregnated bit is a popular tool (Ford Brett et al., 1990). It has a drilling mechanism similar to the PDC bit.

In this paper, we use hard-rock field data from near- and far-offset field three-component (3C) geophones to analyse and compare the energy radiation differences and characteristics of the drilling vibration signal between diamond-drilling and percussion RC drilling during a normal hard-rock drilling process.
5.2 Drilling Methods

5.2.1 Diamond Impregnated Drilling

There are many papers and patents about the different diamond drill-bit designs and their vibration characteristics, such as Ritter (1964), Arceneaux (1979), Langeveld et al. (1992), Atici and Ersoy (2009) and Wang et al. (2011). In our Brukunga experiment, a diamond drill coring bit was used (Figure 5.1). This type of diamond bit has an annular crown and inner and outer concentric side surfaces (Generoux, 1978). The fundamental mechanism used for the diamond bit is rotary drilling. The rotary drill applies a thrust to a bit while a torsional force moves the bit parallel to the rock surface (Maurer, 1966). The interaction of the normal and torsional forces with the rock produces elastic waves in the formation, which can be used for seismic studies. Extensive studies by Sun (1999) have shown that significant differences in acoustic properties can be found among different drilling situations, such as when using a new bit or a worn bit. The study also shows that acoustic signals from worn bits are stronger compared to signals from new bits. Hence, although the driller will try to keep drilling as smooth as possible, the energy from the bit-rock interaction will inevitably change due to varying drilling conditions.
5.2. DRILLING METHODS

5.2.2 Reverse-Circulation Drilling

Reverse-Circulation drilling employs dual-wall drill rods that comprise an outer drill rod and an inner tube. The drilling has pressurised air/fluid that flows internally through the inner annular space of the drill pipe (Marais, 1980; Lang, 1989). When a RC rig is working, the circulating medium (which in most cases is high-pressure fluid) enters the annulus between the rod and tube via the air swivel, which is normally part of the drill string. The air/fluid travels down the annulus to the drilling tool, which is usually a RC hammer, but may also be a blade bit or tri-cone roller bit (see the Brukunga RC drill bit in Figure 5.2). Conventionally, in open-hole drilling, the compressed air powers the drilling tool. The exhaust air carries the cuttings and returns to the surface through the inner tubes in the drill string and rotating head. Once through the rotating head, the air and cuttings change direction at the discharge blast box and are transported through the cyclone. RC drilling is a fast and cost-effective method for mineral exploration while the drilling depth is usually less than 1000 feet (Jonsson, 2005; Bo et al., 2011). Although there are different RC drill designs (Langford Jr, 1976), their working mechanism is basically percussion drilling. As such, the impacts of drilling can be used as an energy source for both drilling and
seismic wave generation (Yokota et al., 2004). The high speed and relatively low cost per meter of RC drilling makes it ideal for obtaining mineral samples in the early phases of an exploration project.

The most important difference between diamond and RC drilling for exploration is the rock sampling. The RC drilling breaks up the rock so it comes up as rubble, while in diamond drilling the rock is retrieved intact (as a cylindrical core). Preservation of the core in an intact form provides additional information about the ore bodies and can also help to better understand the morphology of the structures being drilled. Diamond drilling can also go a lot deeper than RC drilling and is better under certain conditions, including drilling medium to ultra-hard deep geological formations (Bullen, 1985).

5.3 The Experiment

A SWD experiment using both diamond-impregnated drilling and RC drilling was conducted at Brukunga, South Australia. The site is located about 40 km east of Adelaide, in an area of rolling hills in the eastern Mount Lofty Ranges. A main iron-sulphide mineralisation occurs where three conformable lenses are separated by waste beds (Taylor and Cox, 2003).

The drilling program was planned with the drilling direction perpendicular to the mineralisation and the borehole dipping at 60 degrees. Figure 5.3 shows the two rigs at the Brukunga site. They are about 11 m apart, drilling at the same azimuth towards the west.

There were two groups of 3-component geophones deployed for seismic monitoring. One group of sensors was placed near the two rigs while the other group was located far from the rigs (about 250 m). Figure 5.4(a) shows the approximate positions of the 3C sensors at the drilling site. The picture was taken at an early stage of drilling when there was only one rig on site. The near-offset sensors consist of four 3C geophones, named from A to D, which are indicated in dark red in Figure 5.4 (a). The near-offset
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Figure 5.3: Diamond and RC rig at Brukunga

sensor B was attached to the RC drill rig. The four far-offset 3C geophones (A-D) were located in the mine quarry. Three of them, shown in dark blue (Figure 5.4(a)), were positioned in a dry creek, which is at the foot of a 20 m high cliff shown as the light-green line, and the sensor D in dark green is further away at the bank on the far side of a mine pit. In general, the far-offset sensors to the rig were about 250 m away from the rig, and 20 m below the rig elevation. Hence, they were expected to suffer minimal impact from the rig noise interference. The near-offset sensors recorded most of the drill-rig noise as they were located in the drilling yard.

Figure 5.4(b) is the plan view of sensor positions and Figure 5.4(c) is a 3D view of sensor positions as well as the corresponding diamond and RC borehole trajectories. The blue and red colours of diamond and RC boreholes represent the depth intervals where the data were acquired. The RC borehole’s straight trajectory is predicted based on the drilling angle. The data acquired from both drilling techniques are not from the same depth range. This is the result of the RC rig being set up later, when the diamond rig had drilled more than 170 m. The borehole depth range for the diamond drilling data is between 177.4 m to 189.4 m, which corresponds to four three-meter drilling rod lengths. There are three-day long data recorded from RC drilling. During this period the borehole was drilled from the surface to a depth of 90 m.
Figure 5.4: (a) The Brukunga drilling site marked with approximate sensor positions. (b) Plan view of sensor positions. (c) 3D views of sensor positions, and the corresponding diamond and RC borehole trajectories.
5.4 Data Analysis

5.4.1 Raw Data

Figures 5.5 and 5.6 show the diamond and RC drilling raw data recorded progressively with the z-components of the near- and far-offset C sensors, respectively. The diamond-drilling data from a three-hour long coring is shown in Figures 5.5(a) and 5.5(b), while the data from a two-hour long RC drilling session on the first day of the experiment are shown in Figures 5.6(a) and 5.6(b). The raw data records are displayed in one-second lengths along the y-axis. The x-axis is also labelled as progressive time in minutes. For comparison, each figure is normalised with its absolute maximum. Signal amplitude variations are clearly observable in the raw records, with particular contrast notable between drilling and no-drilling background noise.

The Rate-Of-Penetration (ROP) can be estimated based on rod length (3 m rod for diamond drilling, 6 m rod for RC drilling) and recorded drilling time. The average ROP for RC drilling is about 36 m/h and 7.5 m/h for diamond drilling. Other parameters, such as WOB and torque, were not recorded.

For diamond coring, the near-offset sensor C record is shown in Figure 5.5(a), which is located 6 m away from the rig, and about 181 m from the diamond bit. The record of the far-offset sensor C in the quarry is shown in Figure 5.5(b), which is located 117 m away from the rig, and about 129 m from the diamond bit. The drilling signal amplitude variations are small between the drilling records for the four rods. In particular, in Figure 5.5b it is difficult to distinguish drilling signals from the background noise, which manifests the low S/N for diamond drilling.

For RC drilling, Figure 5.6 shows the RC drilling raw data records for the first 30 m of drilling from the same two receivers as shown in Figure 5.5. For the five rods used in the RC drilling, the drill bit penetrates from the surface to a depth of 30 m. As such, the direct distance between the bit and near-offset sensor C increases from 16.7 m to 35.7 m and the distance from the bit to far-offset sensor C decreases from 118 m to 101 m. The moving drill bit results in the signal amplitude variation shown in Figure
Figure 5.5: Recorded diamond drill raw data. One second time length along the y-axis. The x-axis is also time labelled in minutes representing the progressive recording time, corresponding to the increasing depth. (a) Near-offset sensor C z-component raw data record of diamond drilling. (b) Far-offset sensor C z-component raw data record of diamond drilling. Note: rod 2 drilling was stopped in the middle of drilling for retrieving about 1.5 m of cores.

5.6. The amplitudes in Figure 5.6a decrease with the drilling depth, while those of Figure 5.6b increase accordingly.

Figures 5.7(a) and 5.7(b) show the energy changes of the diamond and RC drilling in an alternative way. The energy is computed over a two-second moving window.
Figure 5.6: Recorded RC drilling raw data for first day 30 m drilling. x-axis and y-axis have the same scale as Figure 5.5. (a) Near-offset sensor C z-component RC drilling raw data. (b) Far-offset sensor C z-component RC drilling raw data

Both Figures 5.7a and 5.7b show the far-offset sensor C energy trend in green, and the near-offset sensor C energy trend in blue. Figure 5.7a shows that the energy difference between the two sensors is large, whereas the drilling energy from far-offset sensor C is only slightly higher than the background noise. For diamond drilling, the near-offset sensor C shows dramatic energy changes even within the period of a single rod being drilled. Higher energy is required both at the start and finish for diamond
drilling using a single rod. This may indicate the rig power changes from the driller’s operation; for example, forces ramp up before drill off as mentioned by Langeveld et al. (1992). Figure 5.7b shows RC drilling energy variations for the two C sensors at near- and far-offsets. The near-offset sensor energy decreases, while the far-offset sensor energy increases with drilling depth. This matches the trend from the raw data and is explained by the drill bit advancing deeper and closer to the far-offset sensor C while moving further away from the near-offset sensor C.
The raw data energy analysis above suggests that the recorded signal is from the drill bit of the RC drilling rather than the drill rig. In contrast, the S/N from the diamond drill bit is very low. As the drilling depth increase for the recorded diamond drilling data is small, it is difficult to conclude from the raw data that the slight energy increase for far-offset sensor C (Figure 5.7a) is from the diamond drill bit.

### 5.4.2 Frequency Analysis

The diamond drill-bit vibration signal is related to drill-bit geometry (e.g., the number of cutters on the bit), rotation rate (Gradl et al., 2008), WOB and the rock hardness (Langeveld et al., 1992). An experiment by Gradl et al. (2008) shows there are clear amplitude peaks in the frequency domain for the diamond drill-bit signal, which can be explained by the cutting structure and cutter number. These unique drill-bit characteristics are seen when normalising the rotation rate. However, in our field data there was no rotation information acquired. As such, we use a statistical approach to analyse the signal frequency band. We compare 100 s of drilling and no-drilling data. The amplitude spectrum is computed for each five-second segment of the data, then the continuously computed spectra are combined in a single plot.

For the diamond drilling signal, Figure 5.8 shows the near-offset sensor B (attached to the RC rig) and C (near the diamond rig) signals for no-drilling (a) and drilling (b). For the sensor B (upper row), a low-frequency band of around 50 Hz is not significantly changing with or without the drilling, which may indicate that the sensor is located near a constant vibrating engine or power source. In contrast, the sensor C (lower row) spectra show strong wide-energy bands while drilling, concentrated between 50 Hz and 200 Hz. Unlike the experimental results showing multiple peaks over a wide frequency band by Gradl et al. (2008), in the absence of RPM information, we interpret this as the sensor recording dominant drill-rig vibrations rather than the drill-bit’s signal.

Figure 5.9 compares the RC drilling signal spectra for different sensors. The 100 s of
Figure 5.8: Diamond core drilling at depth about 175 m. Sensor group 5 spectra (located at the drilling yard)

data were recorded at drilling depths from 24 m to 30 m. For the spectra of the near-offset sensor B, Figure 5.9(a) (upper row) shows a low-frequency energy band around 50 Hz while drilling, which is similar to the spectra of the diamond drilling signal shown in Figure 5.8(b). This might indicate that this sensor is under the same noise source interference while drilling using diamond and RC rigs, such as diesel engines. The sensor C (lower row in Figure 5.9(a)) was also located at the rig site, but its amplitude spectra are wide on the three components. The peak is above 100 Hz for the x- and around 100 Hz for the z-component. The different spectra from sensors B
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(a) Sensor group 5, Drilling

(b) Sensor group 4, Drilling

Figure 5.9: Spectra of RC drilling for different 3C sensors

and C (both located at the rig site) may indicate a rig site noise source pattern, or it may be that the periodic rig site noise dissipates quickly. Figure 5.9 (b) shows the far-offset sensors’ spectra, where the noise impact from the rig is lower. The spectra of the far-offset sensor C (upper row) are wide, and the energy concentration is below 200Hz. It actually has information in the same band as near-offset sensor C. This suggests that the RC drill bit is a good vibration source for seismic imaging. The sensor D (lower row) is the furthest from the rig. It also shows the wide spectra, but has some discrete peaks. Its amplitude spectra are not as strong as those of sensor
C, but it still receives sufficient energy from the RC drill bit, particularly considering the local terrain irregularity and the fact that sensor D is about 300 m away from the rig, where the open quarry is between the sensors C and D.

In summary, in the standard operation range (600 to 800 RPM), RC drill bits generate strong wide-band signals and the most significant energy of this drill-bit source concentrates at a higher frequency band than that from standard active seismic sources.

5.4.3 Crosscorrelation Analysis

To perform seismic signal analysis using the energy generated by drill bit, crosscorrelation is a common technique. Crosscorrelating the signal from a reference sensor (pilot) to the receiver array produces a seismogram analogous to a Reverse Vertical Seismic Profiling (VSP) (Rector, 1990; Haldorsen et al., 1995; Mari and Coppens, 2003; Naville et al., 2004; Soma et al., 2004; Yokota et al., 2004; Poletto and Miranda, 2004). Drill-bit interferometry synthesise the recorded passive drill-bit data at any two receivers into waves that propagate between these receivers; one receiver behaves as a source (Vasconcelos and Snieder, 2008a); however this imaging technique requires strict illumination conditions with regards to the source distribution. For our experiment, there is neither a reference sensor nor a regularly spaced receiver array. Using the sparsely placed receivers, the crosscorrelation between two of them recovers the direct signal time delay of the wavefield generated by a source (Lobkis and Weaver, 2001; Weaver and Lobkis, 2006). As such, for the moving drill-bit vibration source, the time delay is related to the bit spatial position changes with respect to the receiver positions.

As the drilling signal is usually contaminated by strong narrow-band noise, the standard crosscorrelation emphasizes this noise. To address this issue and improve the weak energy-band signal, We compare two types of Generalized Cross Correlation (GCC) methods: Roth correlation (Roth, 1971) and SCOT correlation (Carter et al., 1973). Both methods are summarized below.
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For a pilot signal $P(\omega)$ and a geophone signal $G(\omega)$, the crosscorrelation in the frequency domain can be expressed as

$$CC(\omega) = \Psi(\omega)P^*(\omega)G(\omega),$$  \hspace{1cm} (5.1)

where $\Psi$ denotes a weighting function and the asterisk denotes the complex conjugate. If $\Psi = 1$, the equation becomes standard crosscorrelation. For GCC, the weighting function can have the forms:

$$\Psi_{\text{Roth}}(\omega) = \frac{1}{P(\omega)P^*(\omega) + \text{stab}},$$  \hspace{1cm} (5.2)

for Roth correlation and

$$\Psi_{\text{SCOT}}(\omega) = \frac{1}{\sqrt{P(\omega) \cdot P^*(\omega) \cdot G(\omega) \cdot G^*(\omega)} + \text{stab}},$$  \hspace{1cm} (5.3)

for SCOT correlation, where $\text{stab}$ denotes a stabiliser.

By placing the stabiliser term in the denominator of the weighting function, Roth correlation is related to Wiener deconvolution (Wiener, 1964) when the stabiliser is related to the inverse of the S/N (Wikepedia.org, 2015). The stabiliser term in Roth correlations pre-whitens the power spectrum in denominator in order to prevent the instability by small values. The choice of the stabiliser is generally based on trial results. In this case, it is selected as 10% of the mean value of the denominator term in the weighting function. The weighting function boosts the weak signal bands and reduces the amplitudes of the dominant frequency bands so as to improve the cross-spectrum bandwidth.

The SCOT correlation is a cross-coherence method (Aki, 1957; Bendat and Piersol, 2000; Chávez-García and Luzón, 2005). It calculates the crosscorrelation normalised by the corresponding cross-spectral amplitude in the frequency domain; as such, it is able to suppress the influence of additive noise in addition to being able to handle irregular input amplitudes (Nakata et al., 2011). One of the differences between the two GCC methods is that the Roth correlation emphasises the pilot signal band; while
the SCOT correlation uses smoothed coherence by taking into account of both the pilot and the geophone input signals so as to emphasise the phase correlations.

**Correlation using RC drilling signal**

During the three-day period of RC drilling, the drill-bit penetrated from a depth of zero to about 90 m. We use two far-offset receivers C (in the creek) and D (farthest), with C as the reference for crosscorrelation. Figure 5.10 shows the standard and Roth correlation results of the z-components (sensors C and D). The standard correlation result is dominated by strong low-frequency signals.

**Figure 5.10:** Far-offset sensor D (farthest at the quarry) crosscorrelation with far-offset sensor C (in the creek) for 90 m drilling depth. (a) z-component standard correlation. (b) z-component Roth correlation.

Figure 5.11 shows the corresponding SCOT correlation results when using a changing bit depth for the same sensors C and D as in Figure 5.10. Each trace is the correlation result from five-second input data. The continuous correlation is carried out using this five seconds of moving window with 50% overlap. The y-axis is correlation time, and the x-axis is depth of drilling. Based on a RC drilling ROP of 36 m/h with
Figure 5.11: Using the same sensors (C and D) as shown in Figure 5.10 to perform continuous SCOT crosscorrelation. (a) Sensors C and D’s x-component (Easting) correlation, (b) Sensors C and D’s y-component (Northing) correlation. In the blue square we see discontinuity of the data. In the red square we see linear upward moveouts, which are possibly reflections. (c) Sensors C and D’s z-component correlation. Red arrow indicates the drill-bit signal. (d) Sensors C x-component and D z-component correlation. (e) Sensors C z-component and D x-component correlation. (f) Sensors C z-component and D y-component correlation.

A 6 m long rod, the marked depth is approximated under the assumption that the drilling depth increases linearly with time for a single rod. In this figure, we show corresponding crosscorrelations of x-x, y-y, z-z, x-z, z-x and z-y components from sensors C and D. 50 ms anti-causal correlation time is also included in each figure. Comparing these correlations, when using the y-component as the input trace, such as correlation results in Figure 5.11(b) and 5.11(f), the correlation records show a relatively lower frequency band energy than other correlation results. This might indicate the low-frequency SH-wave in the drilling site, but it is not certain that
this wave is emitted from the drill bit. Correspondingly, the high-frequency coherent correlation signal, such as pointed to by the red arrow, could be the drill-bit P-wave signal.

The SCOT correlation weighting function widens the cross-spectrum by using the input trace’s auto-correlation spectra. This technique favors both input signals and does not favor any particular band signals; therefore, a wide-band weak signal becomes distinct. Roth correlation also widens the cross-spectrum, but only by deconvolution of the reference signal power spectrum. As a result, SCOT and Roth correlations are similar however the results from SCOT correlation are relatively noisy. It is understood that SCOT correlation is normalised by both input traces in the frequency domain, so if one input trace is noisier than the other, the SCOT and Roth correlations will produce relatively different results. The anti-causal components in our example can be suppressed by pilot deconvolution as demonstrated by Poletto and Miranda (2004). However, we do not have the true pilot signal recorded and the drill-bit signal could be shown in the correlation anti-causal domain, therefore this technique is not applied to our data.

To interpret the correlation results, we plot the direct distances from the drill bit of RC drilling to the far-offset sensors C and D as shown in Figure 5.12(a). The blue lines that represent the direct distances to both sensors show that the drill bit was moving closer to them; however, the difference between their distances (red line) is small during the drilling period, at around 115 m. As such, the continuous correlation between sensors C and D will result in a near-flat moveout of the correlated drill-bit signal. This flat feature is easily observable in Figure 5.11, particularly on z-component correlation result as pointed out by the red arrow. Stacking of the z-component correlation result improves the picking of traveltime delay, as shown in Figure 5.12(b).

Based on this information, we can estimate the formation velocity in the area. Using 115 m as approximate distance difference, and 19 ms from the flat moveout of the correlation result, then, we can obtain the rock velocity at about $\frac{115\text{m}}{19\text{ms}} = 6050\text{m/s}$. This is a very close match to the P-wave velocity of the core samples measured in the...
Figure 5.12: (a) Direct distance from the drill-bit to far-offset sensors C and D shown as blue lines. The red line is the curve of the distance difference derived from blue lines. (b) Stacked trace of z-component correlation result from Figure 5.11(c). The red arrow indicates the traveltime between sensors C and D.
Other interesting features of the correlations can be observed in the blue and red squares in Figure 5.11(b). The area in the blue square contains weak signals only, which is likely caused by a 20 m high cliff between the rig site and far-offset sensors. The upward moveout shown in the red square for the y-component correlation may correspond to reflections from the mineralisation. This explanation is based on the drill bit moving towards the mineralisation, and with the furthest offset sensor D located in front of the wall of the quarry. The reflected drill-bit signal might arrive at sensor D first, so the reflection signal in the correlation domain (the sensor D correlates against the sensor C) will show a trend of moving to negative times.

Figure 5.13(c) shows the correlation results between the z-component of the far-offset sensor D and near-offset sensor B attached to the collar of the RC rig. Only first-day data are used for correlation, which is only at a drilling depth of 30 m. This is because the other two-day data have a problem synchronisation between near- and far-offset sensors. We show the continuous correlation result of every five second record with 50% overlap. To understand the field data, we built a 2D model as shown in Figure 5.13(a). To simulate the local topography of the mine quarry, there is a pitch and elevation difference shown between sensors B and D. The P-wave velocity is approximated based on the estimation from the far-offset sensor correlation result. The modelling result shows good agreement with the field data in its main features. The time shift between the model and the field data is mainly caused by the more complex topography in the field than that in the model. As pointed out by the arrows, direct P- and S-waves show upward moveout with increasing drill-bit depth. Even during the correlation event between P- and S-waves at the negative time indicated by the blue arrows, the modelling and field data results agree. If this interpretation is correct, this again demonstrates that the recorded signals are generated by the RC drilling drill-bit vibration.
Figure 5.13: Crosscorrelation between z-component signals from near-offset sensor B and far-offset sensor D. The arrows point direct at P- and S-wave. The blue arrow points to P- and S-wave correlation at the negative time. (a) 2D velocity model with 7 shot points along the borehole, (b) C and D correlation result from the model. (c) Field data correlation result from the RC drilling.
Figure 5.14: The z-component crosscorrelation between the far-offset sensors C and D while drilling using the diamond-impregnated bit. (a) SCOT correlation. (b) 100 Hz high-pass filtered SCOT correlation. (c) Stack of the filtered correlations and zoomed-in of the first 100 ms section. 10 ms peak is pointed out by a red arrow.

Figure 5.15: Velocity-time curve for the time delay between sensors C and D, based on source-receiver spatial positions. The red arrow points at the possible drill-bit signal time delay with the local rock velocity at 6000 m/s.

Diamond-impregnated drilling

For diamond-impregnated drilling, the drill-bit signals have significantly lower amplitudes than the signals of RC drilling. Since there is only 12 m depth of recorded
drilling data and the working diamond bit was below 170 m, it is sensible to use far-offset sensors for correlation to minimise the impact of the drill-rig noise. The test of the crosscorrelation between far-offset sensors C and D is shown in Figure 5.14, where each trace is the SCOT correlation result using five seconds of data as input and continuous correlation is performed over a 12 m depth. Figure 5.14 (a) is the SCOT correlation result using the raw data. Figure 5.14 (b) shows the same result, after a 100 Hz high-pass filter.

For the 12 m of drilling at this depth, the distance differences between the working bit to sensors C and D only change from 56 to 64 m. As the source position change with respect to the sensors is small compared to the source-receiver distance, we can treat the drill bit as a stationary source, and stack the correlation result from Figure 5.14(b) along the x-axis. The stacked correlation trace is shown in Figure 5.14(c), along with the zoom-in of the first 100 ms trace. The most significant peak of the stacked trace is at 32 ms. To understand whether the peak is from the diamond drill-bit source, we plot the velocity-time curve based on the distance difference (60 m) between the sensors and the bit as shown in Figure 5.15. The time delay (y-axis) is computed, based on the fixed distances between the diamond drill bit and sensors C and D, for various velocities. It is shown that for a 32 ms drill-bit signal delay from sensor C to D, the corresponding velocity needs to be below 2000 m/s, so this signal peak is unlikely to have originated from the diamond drill bit. A similar stationary event is also observed by Miranda et al. (1996) and Poletto and Miranda (2004), and it is interpreted as the result of refraction of rig-site waves. At the Brukunga mine site, the local rock velocity is about 6000 m/s as derived from RC drilling. In this case, the time delay between sensor C and D from the diamond drill bit is around 10 ms. Although there is a peak at 10 ms in the stacked output (pointed out by the red arrow in Figure 14c), from just a two-receiver correlation result we cannot determine whether this peak is due to the diamond-bit signal. Even assuming this is the bit signal, its S/N is very low for this experiment.
5.5 Conclusions

We compared the energy radiation and seismic signal differences between diamond coring and percussion RC drilling in hard-rock environments. By investigating the three-component geophone signal from near- and far-offset sensors, we show that the drilling signal is complicated and very different between diamond and RC drilling. When the drill string rotation rate ranges from 600 to 800 RPM, the drill bit from RC drilling generates significantly higher energy compared to the diamond-coring drilling. Its peak energy concentrates above 100 Hz, which is higher than most of the noise band generated from the rig site in our experiment. Crosscorrelation also confirms the reception of the drill-bit signal from RC drilling, and the local rock velocity can be estimated from just a two-sensor correlation. Overall, the signal recorded by RC drilling will be suitable for drill-bit seismic imaging purposes. In contrast, the diamond drilling does not have adequate energy for analysis with only a few sparse receiver positions.

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Chapter 6

Conclusions
My research focuses on a feasibility study of SWD in hard rock drilling environments. The advantages of SWD have been recognised in the petroleum industry where there are many successful case studies of its application. Its successful application provides the potential to image around or ahead of the drill bit as well as check-shot-like surveys, but these advantages were not explored previously in the mining industry. The main reason for this is that there is a dominant use of diamond-impregnated drill-bits in hard rock drilling, which is a quiet seismic source. Therefore, most of my thesis is aimed at investigating the possibility of capturing the diamond drill-bit signal with a surface receiver array, which has not been studied in previous literature.

I have demonstrated the application of using the diamond drill-bit direct wave to estimate the overburden velocity and image the drill bit position. Potentially, it may also be used to infer the wear rate of the drill bit by studying the bit vibrations due to the bit-rock interaction. There are two sets of field experiment data acquired from the Brukunga and Hillside mines in South Australia, respectively. For each experiment, I have worked through acquisition, processing and data analysis and strive to use unconventional methods to deal with the challenge of detecting the weak drill-bit coherent signal recorded from a surface receiver array. This thesis has presented a variety of approaches of applying various signal detection methods to synthetic data as well as the two field data sets.

From the Brukunga SWD experiment, although we had a 3D array for data acquisition, the receivers were not deployed at the best positions for signal detection due to the difficult topography. As a result, the outcomes from the experiment didn’t meet our expectations. The spectrum of the drilling data record at the surface is wide, but with strong discrete peaks. Those narrow-band peaks are considered to be strong interference noise from the drill site and therefore it is difficult to distinguish the drill-bit signal in the frequency domain. These narrow-band peaks also caused the low temporal resolution while using standard crosscorrelation. The dominant peaks become more prominent due to the band-pass filter result after correlation. Therefore, to see a wider bandwidth signal, which may include the weak drill-bit signal, the GCC techniques were investigated. There are various forms of GCCs, but all utilise
different deconvolution filters in the correlation domain. The cross-spectrum can be effectively widened after this process and correspondingly, the time domain resolution is improved. Various tests and discussions relating to the synthetic and field data are shown in Chapter 2.

Another outcome from the Brukunga experiment is the rig wavefield suppression for SWD. There is strong drill-rig-generated interference noise in the data from this experiment. This was observed through the signal analysis of the raw data energy variation, the signal spectra, and the correlation tests. As a result, there are no clearly visible drill-bit signals. Therefore the suppression of strong drill rig noise may help improve the drill-bit signal detectability. This can be achieved based on the different wavefield characteristics of the drill rig and the drill bit due to their spatial position differences. While drilling, the drill-bit’s position changes, but the drill rig remains stationary. This allows us to separate and extract the drill-bit signal. In Chapter 3, I demonstrate the use of Karhunen-Loéve transform to separate the possible drill-bit wavefields. I have shown that this method is very effective and has little or no contamination to the desired drill-bit wavefield when it is applied in a common receiver gather. This advantage is compared and demonstrated against the f-k filter, but in a common shot gather the f-k filter may achieve a better result. The application of the KL transform in a receiver gather raises a need for the continuous acquisition of drilling data. This is to ensure that the different wavefield moveouts emitted from the rig and bit are recorded. Unfortunately, after the suppression of the rig noise from Brukunga data, the diamond drill-bit signal is still very difficult to observe in this experiment. Besides the low radiation energy from the drill-bit, the unknown radiation pattern of the drill-bit signal and non-optimally positioned receiver array may also lead to this result.

Based on the understanding of possibly very low energy of the drill-bit wave field on the surface receiver array, I compared weak coherent signal detection methods, semblance and MUSIC. Synthetic examples are used to demonstrate the differences by imaging using coherency measure under varying situations, such as timing errors. The MUSIC coherency shows higher spatial resolution compared to semblance while
imaging a buried source. The resolution and signal detectability by MUSIC can be controlled by the signal space dimension. With added coherent noise and large wavefront time errors, MUSIC still produces robust measurements when compared to semblance. In general, when using MUSIC coherency, by increasing the dimension of signal subspace one can increase the signal detectability by tolerating less-coherent events, but this results in reduced resolution. Therefore, MUSIC coherency can serve as a good complement to semblance for improved image resolution.

One of the applications of a coherency measure in SWD is to estimate the overburden velocity by scanning the drill-bit direct wave. The expected outcome from SWD velocity analysis is to replace the check-shot survey with sonic log calibration. Also, an improved velocity model around the bore hole can be very important for drilling engineers and geophysicists, so they can gain a better understanding of the local geology. The velocity estimation is done by scanning the coherent moveout, which is done in the correlation domain. In chapter 4, the method is demonstrated on a synthetic model. Using field SWD data from Hillside in South Australia, a consistent velocity information is obtained, which broadly agrees with acquired reflection and refraction velocities at a nearby survey. This outcome is achieved with a diamond impregnated drill-bit drilling survey at relatively shallow depths. We expect this method to be even more successful with other more noisy drilling techniques, such as percussion drilling and could be used for deeper drilling experiments.

The other application of using the drill-bit direct waves is to image the drill-bit location. Interferometric migration is a passive seismic imaging method that can be used for reflectivity and source-position imaging. For diamond drill-bit radiated energy, sufficient reflectivity is difficult to achieve; as such, just the source position imaging is implemented in Chapter 5. Conventionally, interferometric imaging uses summation as the migration operator. In this chapter, I demonstrate the use of coherency measurement, semblance and MUSIC during migration for improved signal detection. The coherent measurement can be effectively employed in the migration process without much increase from the computation time. I demonstrated this migration applied on Hillside SWD data. The coherent interferometry migration is able to image the
drill-bit position. It achieved a good spatial resolution of the drill bit, particularly with the MUSIC method.

To compare the different drill-bit energy radiation from different drilling mechanisms, an experiment was performed using sparse 3C receivers to acquire both the diamond and RC drilling signal at Brukunga. The results are shown in Chapter 6. The two drilling mechanisms generate very different seismic responses. The signal analysis of the 3C geophones from near- and far-offset show that the drilling signal is very different between diamond and RC drilling. At a normal hard-rock drilling rotation rate from 600 to 800 RPM, the energy generated from the drill bit of RC drilling is significantly higher, in contrast to the diamond bit energy. Cross-correlation tests confirm the reception of the drill-bit signal from RC drilling and estimation of local rock velocity can be implemented from just a two-receiver correlation. Therefore, the signal recorded by RC drilling might be suitable for drill-bit seismic imaging purposes. In contrast, when drilling is carried out with a diamond drill bit using the same receivers on the site, there is no convincing visible drill-bit signal observed in the experiment, as shown in Chapter 6.

This thesis has demonstrated the feasibility of using the diamond drill-bit vibration as a seismic source. Although I have shown the diamond impregnated bit signal can be detected by a surface receiver array at a shallow drilling depth, it still cannot achieve its full promise for imaging ahead of, or around, the bore hole. The working diamond drill-bit vibration is still weak, even in hard-rock drilling. This is demonstrated through various methods and attempts at detecting weak coherent signal from the drill bit. However, this thesis demonstrates that the use of more noisy drilling techniques, such as RC drilling, could achieve the expected imaging results.

This thesis has also highlighted the future research for studying the application of SWD in mineral exploration, such as the use of downhole receivers to record the weak drill-bit signal. The techniques studied in the thesis, such as MUSIC and KL transform, can be directly applied in other SWD experiments.
Appendix A

A software summary – SWDVS

One of the side products of my research is the following software package, called SWDVS. I believe this software can be useful for some basic seismic processing and visualisation with Matlab, so I have made it freely available to all researchers. This software can be considered as add-on to Matlab. Its feature is fast processing or visualisation of a workspace matrix. The source codes can be downloaded from Sourceforge, https://sourceforge.net/projects/swdvs/. Herein, I outline some basic functionalities of SWDVS. I briefly describe the software interface as follows.

Figure A.1: SWDVS main interface.
Open SWDVS

To start the SWDVS, just add SWDVS and its subfolders to Matlab search path, then type SWDVS in the command window, then Figure A.1 should appear as the main interface. It consists of four main parts.

**Workspace** points to the Matlab work space. The 'var list' button is used to refresh the workspace variables. The 'var info' button obtain information about the current variables. The 'X' button is used to delete a variable.

**Data section**

The data section appears on the top-right corner of the interface. SWDVS is able to load Matlab, SEGY and SEG2 formats. The current loaded dataset will appear in the Trace Name field. For the SEGY data format, data is loaded into a structure array, which includes headers and data separately as cells. It is certainly possible to change this into separate header and data fields. The **Data Range** is also located in the Data section. This section allows the choosing of a seismic data trace range for processing or plotting, there are two time ranges available. To activate the second time range, just tick the '2nd t' box. This is useful for comparison between traces with different time sections, for example in checking SWD drilling and non-drilling data.

Data is imported from the **Data** menu. For our SWD experiment, the continuous recorded data from Seistronix Ex6 Crf files can be imported from here. The importing parameters are shown in Figure A.2. For some format data, such as Crf data, the header information is incorrect, so one needs to define these parameters. This includes:

- Chan Qty - how many usable channels on line, but it is not necessary all active channels,
- File Qty - how many files generated by continuous recording under one folder,
- Cat & Convert - concatenate and convert files into a struct structure in Matlab.

Note: you need to manually adjust the code to allow output using only active channels.
• Update headers - load a xsl file into the header array, Excel needs to be manually input.

Data can also be saved to disk using 'Export' from the 'Data' menu. The data can be saved as a SEGY file.

Figure A.2: (a) Data-loading parameter window. (b) Data export.

The **Signal processing** section is used for some basic processing routines. Input data is defined by a 'data range' and currently, you can apply 'remove dc', 'normalisation', 'band pass filter', 'notch filter', 'kill traces' and so on. The processing can be applied in order from 'P1' to 'P6'. You will need to assign an output name for the process output or it will use a default name.

**Plotting** functions takes up most part of the interface, which is further divided into plotting in the time and frequency domains. Some example plots are shown in Figure A.3. Some short-cuts to tweak the display include:

• Ctl+L, localise wiggle traces,

• Ctl+G globalise wiggle traces,

• Ctl+U increase the scale of wiggle traces,

• Ctl+D decrease the scale of wiggle traces.

These controls can also be implemented from the Plot menu. While on the display, one can interactively see a single trace amplitude spectrum or multiple trace average
amplitude spectra by selecting 'Tool', 'Spectrum' or 'Power Spectrum'. An example is shown in Figure A.4, which is from the SWD Brukunga data.

Other general plotting functions include, display multiple traces in one figure, and in the frequency domain one can display a single trace spectrum or power density spectra. If there are two time ranges input from a data range, the display will show them in one window as comparison, such as in the Figures A.5 (a) and (b).

Another example of plotting is shown in Figure A.6. It is an FX plot with columns of each trace spectrum display.

Other than plotting and some processing, one can apply various type of correlation
operations. This feature is used to deal with passive drilling data. The standard crosscorrelation usually does not work with these data due to strong narrow-band signal interference. This dialogue can be accessed via the ‘Processing’ ⇒ ‘Correlation’ menu. Input data and time in crosscorrelation is loaded based on the data range from the main interface, but one needs to specify a pilot trace and other traces for correlation. You can use a different stabiliser and smoothing window length. Currently, it can perform a normal crosscorrelation, Roth, SCOT and PHAT correlation.
Figure A.6: FX plot.

Figure A.7 shows the correlation interface. The correlation control panel is on the left, where we can also control which traces to display in the right panel. On the right, it shows three traces, including the correlation input pair on the top two (a reference trace and an input trace) and the bottom is the correlation results. The correlation results will be found in the main workspace after closing the interface.

Hodogram analysis for the 3C-component can be done via the 'Processing' 'Hodogram
menu. It will prompt you to enter three traces, then a window will appear like Figure A.8(a). You can control the time range for plotting as well as input two time ranges to compare. An axis scale may be used to control the display scale on each window, such as in Figure A.8(b).

![Hodogram](image)

Figure A.8: Hodogram.

Some other functions that may be used with this package include a base map plot, Tri-Axial drill-bit (TAD) VSP, and a KL transform. I believe that adding more function modules is relatively easy. In this package, each single function can be called directly from Matlab, so even without the interface, these codes can also be useful.
Appendix B

Copyright Release Information

Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.
Dear Baichun,

You have my permission to include in your thesis all the papers that I co-authored with you.

Regards,
Andrei

Andrei Bona
PhD
Associate Professor
Department Exploration Geophysics | Western Australian School of Mines
[Postal Address: GPO Box 11,897, Perth, Western Australia, 6845, (813. 2044)]
[Street Address: APE/CSIRO Building, H Block, Level 4, 26 Dick Perry Avenue, Kensington 6151, Western Australia]
Tel | +61 8 9266 7194
Fax | +61 8 9266 3407
Email | andrew.king@csiro.au
Web | www.geophysics.curtin.edu.au

--- Original Message ---
From: baichun (baichun@student.curtin.edu.au)
Sent: Tuesday, 7 October 2014 11:19 PM
To: Andrei Bona, Andrew King (Contact: King, Andrew (Energy, Kensington); Zhou, Binzhong (Energy, Pullenvale))
Cc: Andrei Bona

Hi Baichun,

You have my permission to include this paper in your thesis.

Regards,
Binzhong

Hi, Baichun.

I have to ask for permission to include this paper as part of my thesis.
If you are happy with it, please give me a yes.

Thanks,
Baichun
Hi Baichun,

I am happy for you to use any paper that I've co-authored with you for your thesis.

Regards,
Andrew

On 2014/10/07, at 11:19 am, baichun <14257722@student.curtin.edu.au> wrote:

Hi all.

I have to ask for permission to include this paper as part of my thesis. If you are happy with it, please give me a yes.

Thanks,
Baichun
From Andrej Bona

Subject: Re: Permission to use GEO-2014-0344 as part of my thesis

To: Ms <14257722@student.curtin.edu.au>
Cc: Binzhong Zhou@csiro.au, Zhou <Binzhong Zhou@csiro.au>, Andrej Bona@, Matt Vandewerk@csiro.au

Dear Baichen,

You have my permission to include in your thesis all the papers that I co-authored with you.

Regards,
Andrej

Andrej Bona
PhD
Associate Professor
Department Exploration Geophysics | Western Australian School of Mines
Postal Address: GPO Box U1987, Perth, Western Australia, 6845 | Eld 613, Rm 404
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Email: A.Bona@curtin.edu.au
Web: www.geophysics.curtin.edu.au

-----Original Message-----
From: Baichen <baichen.14257722@student.curtin.edu.au>
Sent: Tuesday, 7 October 2014 1:15 PM
To: Zhou, Binzhong (Energy, Pullenvale)
Cc: Bona, Andrej [Curtin (Eng)]. Contact: Van De Merksen, Matt [Energy, Pullenvale]
Subject: Permission to use GEO-2014-0344 as part of my thesis
Hi All,

I have asked for permission from each author of the paper in order to include it as part of thesis. If you are happy with it, please give me a yes.

Thanks,
Baichen

-----Original Message-----
From: Matt Vandewerk@csiro.au
Subject: Re: Permission to use GEO-2014-0344 as part of my thesis
To: Ms <14257722@student.curtin.edu.au>, Zhou, Binzhong@csiro.au
Cc: Andrej Bona@ csiro.au

Hi Baichen,

You have my permission to use this paper in your thesis.

Cheers,
Matt.
Dear Baichun,

You have my permission to include in your thesis all the papers that I co-authored with you.

Regards,
Andrei

Andrei Bona
PhD
Department Exploration Geophysics | Western Australian School of Mines
[Postal Address: GPO Box U1987, Perth, Western Australia, 6845] [Bld 613, Ph 404]
[Street Address: ARRC/CERTO Building, H Block, Level 4, 26 Dick Perry Avenue, Kensington 6151, Western Australia]
Tel | +61 8 9269 7194
Fax | +61 8 9266 3407
Email | A.Bona@curtin.edu.au
Web | www.geophysics.curtin.edu.au
On 7 April 2014 at 11:54 am, Baichun Zhou@student.curtin.edu.au wrote:

From Anton Kepic <A.Kepic@curtin.edu.au>
Subject: RE: Permission to EG14035-R1 as part of my thesis

Yes.

Anton Kepic

Associate Professor
Department of Exploration Geophysics

Curtin University
Tel | +61 8 9266 7503
Fax | +61 8 9266 3407
Mobile | 0427 191 881

Email | A.Kepic@curtin.edu.au
Web | http://curtin.edu.au
Hi Beichun,

You have my permission to include this paper in your thesis.

Regards,
Binzhong

-----Original Message-----
From: Beichun sent: Tuesday, 7 October 2014 1:34 PM To: Bona, Andrej (Curtin Uni) - Contact: Zhou, Binzhong (Energy, Pullenvale); King, Andrew (Energy, Kensington); Subject: Permission to EG14035-R1 as part of my thesis

Hi All,

I have to ask for permission from each author of the paper (it is sent to EG for review now) in order to include

Thanks,
Beichun

On 2014/10/08, at 9:31 pm, Beichun Sun <14257722@student.curtin.edu.au> wrote:

Hi Andrew / Christian,

Would you please let me know if you are ok for me to include this manuscript EG14035-R1 (submitted to Exploration Geophysics) as part of my thesis?

Cheers,
Beichun

On 2014/10/08, at 9:30 AM, "Beichun Sun" <14257722@student.curtin.edu.au> wrote:

Hi Andrew / Christian,

Would you please let me know if you are ok for me to include this manuscript EG14035-R1 (submitted to Exploration Geophysics) as part of

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Best of luck with your thesis, and thank you for your submissions to Geophysics.

Sincerely,

Ted

--
Ted Bakamjian, IOM CAE
Director, Publications
Society of Exploration Geophysicists
P. O. Box 702740, Tulsa, OK 74170-2740 USA
Shipping: 8801 S. Yale Ave., Suite 500, Tulsa, OK 74137
Phone: (918) 497-5506; Fax: (918) 497-5557
Web: http://www.seg.org/
SEG Digital Library: http://library.seg.org

On Sep 29, 2014, at 9:32 AM, Baichun Sun <baichuns@gmail.com> wrote:
Subject: Re: permission enquiry
From: Ted Bakamjian <Tbakamjian@seg.org>
Date: 14/10/14 11:09
To: Baichun Sun <14257722@student.curtin.edu.au>

Dear Baichun,

Permission is granted. Please provide a standard citation to the source article, including the permalink:

http://dx.doi.org/10.1190/1.1897039

Best of luck with your thesis.

Sincerely,

Ted

--
Ted Bakamjian, IOM CAE
Director, Publications
Society of Exploration Geophysicists
P. O. Box 702740, Tulsa, OK 74170-2740 USA
Shipping: 8801 S. Yale Ave., Suite 500, Tulsa, OK 74137
Phone: (918) 497-5506; Fax: (918) 497-5557
Web: http://www.seg.org/
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On Oct 7, 2014, at 8:51 AM, Baichun Sun <14257722@student.curtin.edu.au> wrote:

Dear Sir / Madam,

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The specific figure that I would like to use for the purpose of the thesis is:

Fig 1 (a) Milled roller-cone bit used in softer and shallower formations. (b) Insert roller-cone bit used in deeper and harder formations.
Hi Baichun,

there are no issues (assuming it is clearly stated as such), it is quite common for students to have submitted papers and also have that paper as a chapter in their thesis.

All the best with your thesis.

cheers

Mark

On 30 September 2014 00:37, Baichun Sun <baichuns@gmail.com> wrote:

Dear Dr lackie,

I am writing to ask for permission to use a paper submitted to Exploration Geophysics as part of my thesis.

The submitted paper is:

Drill-rig noise suppression using the Karhunen-Loeve Transform for Seismic-While-Drilling Experiment at Brukunga, South Australia (EG14035)

My revision is submitted for review at this stage. I wonder if there are any issues for me to include this in my thesis.

Kind Regards,
Baichun

--

Dr Mark Lackie
Senior Lecturer in Geophysics
Department of Earth and Planetary Sciences
Macquarie University
North Ryde NSW 2109
Ph 61-2-98508377  Mob 0425237899
Fx 61-2-98506904
Subject: RE: Permission to use boartlong bit categorlogy figure in PhD thesis
From: "Portman, Monika" <monika.portman@boartlongyear.com>
Date: 10/06/2014 10:31 PM
To: baichun <14257722@student.curtin.edu.au>

Barry,

We are fine with you using these illustrations. Thanks!

Monika Portman
Director – Product Management, Marketing,
and Corporate Communications
10808 River Front Parkway
Suite 400
South Jordan, UT 84095
Office 801-952-8451
Mobile 801-608-8329

From: baichun [mailto:14257722@student.curtin.edu.au]
Sent: Wednesday, October 01, 2014 9:55 PM
To: Portman, Monika
Subject: Permission to use boartlong bit categorlogy figure in PhD thesis

Dear Monika,

I am writing to ask for permission to use two figures from boartlongyear 2009 categorlog. Please see the figure below, and full reference has been made.

I am currently doing PhD in curtin University from Australia. My PhD thesis is about seismic-while-drilling. That is why I need to demonstrate the diamond drill-bit in my thesis. These are the only two being used.

Best Regards,
Barry
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