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# Seismic Signal Processing for Single Well Imaging Applications

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*Brendan Walsh*



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# Abstract

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This thesis focuses on the concept of Single Well Imaging (SWI) in which a seismic source and receivers are deployed in a borehole to investigate the surrounding geology. The Uniwell project (1997-1999) was the first attempt to develop the SWI method; it used a fluid-coupled downhole source, which unfortunately generated high amplitude guided waves in the borehole which obscured all other useful information.

Initial research work detailed in this thesis focused on removing the high amplitude guided waves, known as tube waves. Two-step source signature deconvolution using first the recorded source signature, and then the tube-wave reflected from the bottom of the well, succeeded in compressing the tube wave. The results were not consistent across all receivers, but there is enough correlation to identify a P-wave. Further work concentrates on using a new technique called Empirical Mode Decomposition to separate the tube-wave mode from the data. This identifies three dominant modes and a possible body wave arrival, but the results are ambiguous due to the inability of the decomposition to focus on the narrow bandwidth of interest.

The source signature deconvolution technique can also be used to process real-time vertical seismic profiling (VSP) data down-hole, during pauses in drilling, in what is referred to as a Seismic-While-Drilling (SWD) setup. Results show that the technique is versatile and robust, giving 1 ms precision on first-break picking even in very noisy data. I also apply the technique to normal VSP data to improve both the resolution and the signal-to-noise ratio.

A major effort in this thesis is to consider the effect of a clamped downhole source to overcome the tube-wave problem, using a magnetostrictive source. Earlier work established that the use of a reaction mass tended to excite resonances in the tool which caused the transducer to break. A new design for the source was developed in cooperation with colleagues which utilises a hydraulic amplifier design and a low power coded waveform driving method exploiting the time-bandwidth product to extract the signal from the noise. My results show that as the run time increases the resolution improves. With a run length of 80s it is possible to resolve the signal transmitted 50 cm through a granite formation. This analysis led to a revised design of the source to improve its efficiency.

I have used finite difference modelling, with a variable grid technique, to compare an ideal explosive source with an ideal clamped source. The fluid-coupled source emits high amplitude tube waves which virtually obscure the body wave, whereas the clamped source emits a clearly identifiable P-wave along with lower amplitude tube waves. This clearly illustrates the advantage of an ideal clamped source. To model the source more accurately the ideal

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wavelet is replaced by the respective recorded source signatures, and the data is then processed by cross correlation with the appropriate signature. The results show that the coded waveform approaches the resolution of the ideal wavelet very well, with all major events being visible. However, the fluid-coupled source performs very poorly with only the highest amplitude tube-wave visible.

This work illustrates that by replacing a fluid-coupled source by a clamped source driven by a coded waveform, and by processing the data using cross correlation or signature deconvolution, it is possible to minimise or eliminate tube-wave noise from a SWI survey. It is hoped that the results outlined here will provide the basis for a new SWI method than can be used to prolong the supply of North Sea oil.

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## Declaration of originality

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I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the Department of Electronics and Electrical Engineering at The University of Edinburgh.

The software used was written by myself with the exception of the finite difference code (which was kindly provided by Prof. Thomas Bohlen, The University of Kiel), and the subroutines used to process the Uniwell data, which were written by Professor Anton Ziolkowski. In addition the initial work on the mechanical design of the magnetostrictive source was conducted by Professor Steven McLaughlin, Professor Anton Ziolkowski, Dr. Jimmy Drips and Alastair Brand.

Brendan Walsh

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# Acknowledgements

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No man is so foolish but he may sometimes give another good counsel, and no man so wise that he may not easily err if he takes no other counsel than his own. He that is taught only by himself has a fool for a master. - *Hunter S. Thompson*

I would like to thank Professor Anton Ziolkowski and Professor Steven McLaughlin for all the support, advice and encouragement they have given me over the years, and for all the great discussions we have had. I would also like to thank Dr. Jimmy Dripps, Alistair Brand, Margaret Bayne and Nicola Ferguson for all their help throughout my studies.

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## Acronyms and abbreviations

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|      |                                       |
|------|---------------------------------------|
| 3G   | 3rd generation                        |
| AC   | Alternating current                   |
| ADC  | Analog to digital converter           |
| BHA  | Bottom hole assembly                  |
| CCW  | Counter clockwise                     |
| CFG  | Course to fine grid transition        |
| CPU  | Central processing unit               |
| CW   | Clockwise                             |
| DAS  | Data acquisition system               |
| DC   | Direct current                        |
| DOV  | Downhole orbital vibrator             |
| DSSS | Direct sequence spread spectrum       |
| DTI  | The UK Department of Trade and Energy |
| EGG  | Electro-cardiogram                    |
| EMD  | Empirical mode decomposition          |
| FDTD | Finite difference time domain         |
| F-K  | Frequency wave number                 |
| GB   | Gigabyte                              |
| GPS  | Global Positioning System             |
| GSLS | General standardised linear solid     |
| IMF  | Intrinsic mode function               |
| kB   | Kilobyte                              |
| LAN  | Local area network                    |
| LBNL | Lawrence Berkeley National Laboratory |
| MPI  | Message passing interface             |
| NMO  | Normal move-out                       |
| OVS  | Orbital vibrator source               |
| PVDF | Polyvinylidene Fluoride               |
| PRBS | Pseudo random binary sequence         |

|     |                                      |
|-----|--------------------------------------|
| QC  | Quality check                        |
| RF  | Radio frequency                      |
| RMS | Root mean square                     |
| SEG | Society of Exploration Geophysicists |
| SH  | Horizontal shear                     |
| SSG | Standard staggered grid              |
| SS  | Spread spectrum                      |
| SV  | Vertical Shear                       |
| SWD | Seismic while drilling               |
| SWI | Single well imaging                  |
| VSP | Vertical seismic profiling           |
| TB  | Time bandwidth product               |
| TWS | Tube wave suppression                |

---

# Nomenclature

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|               |                                                             |
|---------------|-------------------------------------------------------------|
| $\alpha_i$    | P-wave velocity in the medium                               |
| $\alpha_f$    | P-wave velocity in the fluid                                |
| $\beta_i$     | S-wave velocity in the medium                               |
| $\delta$      | Angle between K and the z - axis                            |
| $\epsilon$    | White noise                                                 |
| $\gamma$      | Ratio of S-wave velocity to P-wave velocity in the medium   |
| $\lambda$     | First Lamé coefficient                                      |
| $\mu$         | Second Lamé coefficient                                     |
| $\omega$      | Radial frequency                                            |
| $\sigma_{xx}$ | Normal stress in the $xx$ direction                         |
| $\sigma_{zz}$ | Normal stress in the $zz$ direction                         |
| $\sigma_{xz}$ | Normal stress in the $xz$ direction                         |
| $\rho_f$      | Density of the fluid                                        |
| $\rho_i$      | Density of the medium                                       |
| $\Sigma$      | Stress, in the discretised numerical domain $xx$ direction  |
| $\Xi$         | Stress, in the discretised numerical domain, $zz$ direction |
| $\Omega_i$    | $\frac{\omega_{rh}}{\beta_i}$                               |
| $\Phi_i$      | Scalar potentials                                           |
| $\Psi_i$      | Scalar potentials                                           |
| $a$           | Cross section area of actuator push-rod                     |
| $b(x, z)$     | Buoyancy or lightness                                       |
| $h$           | Thickness of the tube                                       |
| $k$           | Bulk modulus of the liquid or wavenumber                    |
| $r$           | Distance traveled by the direct wave                        |
| $rg$          | Distance traveled by the reflected wave                     |
| $v$           | Velocity vector                                             |
| $v_f$         | Particle velocity in the fluid                              |
| $v_t$         | Tube wave velocity in the fluid                             |
| $A$           | Cross section area of clamp                                 |

|         |                                                                                                       |
|---------|-------------------------------------------------------------------------------------------------------|
| $B$     | Bulk modulus                                                                                          |
| $C_t$   | Tube wave velocity                                                                                    |
| $E$     | Young's modulus                                                                                       |
| $H_v^i$ | Hankel function of the $i$ th kind of order $v$                                                       |
| $J_v$   | Bessel function of the order $v$                                                                      |
| $L$     | Lame coefficient in the discretised numerical domain                                                  |
| $M$     | Lame coefficient in the discretised numerical domain                                                  |
| $P$     | Pressure                                                                                              |
| $U_x$   | Particle displacement vector in the $x$ direction                                                     |
| $T$     | Shear component of the stress tensor, equivalent to $\sigma_{xz}$ in the discretised numerical domain |
| $V_s$   | Shear or S wave speed                                                                                 |
| $V_p$   | P or compressional wave speed                                                                         |

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# Chapter 1

## Introduction

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The use of boreholes in exploration seismology has developed dramatically since Fessenden's patent of 1917, which was effectively the first documented seismic application using buried sources and receivers. In his patent Fessenden outlines the method. This consists of two fluid-filled boreholes, with a source in one and two receivers in the other (Figure 1.1). He describes a method to locate a buried ore body: 'the vertical angle of reflection may be determined by hauling the transmitter 49 or the receivers 18, 15 up or down in the drill holes' [32]. Despite Fessenden's patent and subsequent papers by Barton [4] and McCollum et al. [51], which described how this new method could be effectively used, the field of borehole seismology was generally ignored by the geophysical community at the time, who preferred to rely on more familiar, surface based methods.

However, at the beginning of the 1970s Soviet geophysicists, notably Gal'perin [29], began to publicize the usefulness of the method; subsequently non-Soviet geophysicists eventually began to take interest. Technical conferences and continuing education courses in the late

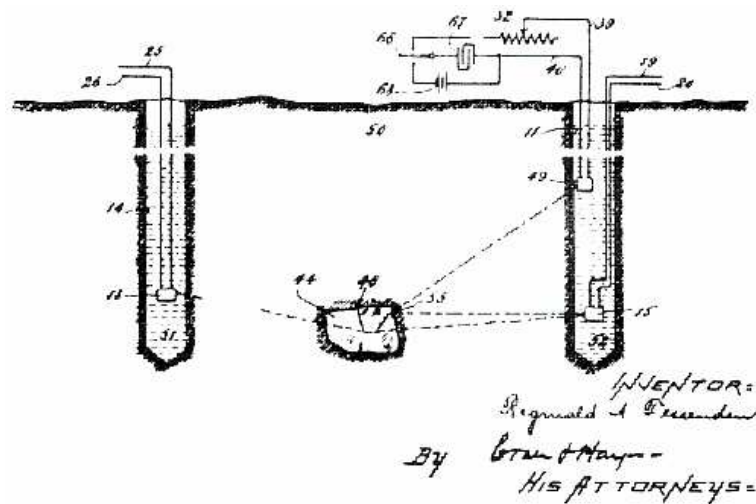


**Figure 1.1:** Diagram from Fessenden's original patent application. Showing his idea for the method that would become known as VSP. Taken from Hardage [32]

70s and into the early 80s helped to build a foundation and understanding of the method now referred to as Vertical Seismic Profiling or VSP as a result of these conferences and courses, industry interest in this new technology began to grow. Some of the earliest spokesmen for VSP, where Kennett & Ireson [38], Michon [53], Omnes [57], Balch et al. [3] and Anstey [1]. Balch and Lee [3] published one of the first books on the method, which included case studies of various experiments, and also brought together the theory of borehole seismology, which had previously been outlined in detail by White [79] and Schoenberg [66]. Hardage [32] published a comprehensive practical guide to the subject. Both books came out at a time when papers on VSP theory and published experiments were rare.

Since this point in the early 1980s, VSP and its variations have become widely established. Despite the great technological and theoretical advances made by the previous authors it was not until the late 1990s that serious research time was spent investigating a different method from that described by Fessenden. This new method was called Single Well Imaging (SWI) and was similar to sonic logging. Ziolkowski et al. [83] at the University of Edinburgh was one of the first advocates of this method. In the 'Uniwell' experiment they placed the source and receiver in the same hole, using the same wireline. Three-component geophones recorded the full particle motion of the surroundings as shown in Figure 1.2. Ziolkowski et al. [84] carried out two experiments at the Humble Test Site, near Houston, Texas, using this new method in conjunction with a more standard crosswell set-up. Using the data recorded from the crosswell set-up, they were able to image a steeply dipping reflector in three dimensions.

When they attempted to use the Uniwell data to image the reflector, the scattered waves and even the first arrivals of the body waves were completely obscured by a coherent noise event. This coherent noise is known in VSP and SWI as a tube wave, a non-dispersive guided wave with effectively one-degree of freedom that travels up and down the axis of a fluid-filled borehole and between the borehole casing and formation, as described by White [79]. As a result of their non-dispersive nature [68], the amplitudes of these wave modes stay relatively high as distance from the source increases, while the body waves experience spherical divergence. Due to these characteristics tube-wave noise cannot be removed by stacking, although this can be used to enhance the tube-wave before attempting to remove it.

The need for a new method such as SWI comes from the current problem with finding and replacing existing oil and gas reserves. One of the reasons for this is that most of the

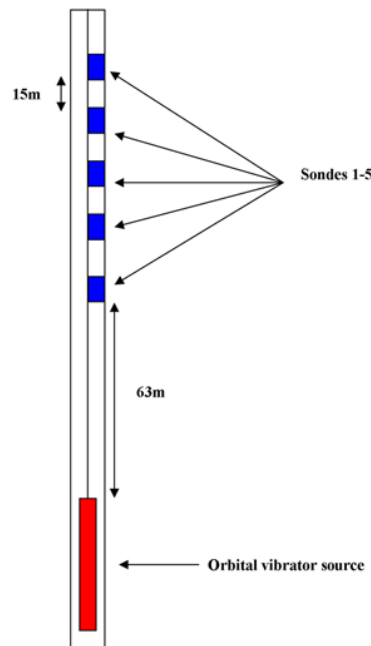


**Figure 1.2:** *Single well imaging setup as used in the Uniwell experiment.*

massive oilfields have been discovered, especially in the North Sea. What remain are smaller fields which are more difficult to image. Stratigraphic traps are a perfect example of this. Since exploration started in the North Sea almost all of the stratigraphic traps that have been discovered, were found by chance whilst drilling for other targets.

At present the relatively low resolution of surface based methods and processing methods which distort both the wavelet and the phase of the data makes it difficult to positively identify small features, such as stratigraphic traps. It is almost always possible, to obtain an accurate measurement of the source signal [85], yet this is almost never done, or if it is, the signal is only used as a time break, or for QC of the airguns. The reason given is generally cost, yet it would amount to less than 1% of survey costs, and could lead to fewer dry wells being drilled if the source signature was recorded and used to process the data. Without knowledge of the source signature the only option is to estimate it from the data. There are countless methods to do this. However, each method yields a different result, making it impossible to arrive at a deterministic interpretation.

## 1.1 Contributions to knowledge

The aim of the research outlined in this thesis was to develop a framework of solutions to overcome the problems that have prevented SWI becoming a usable technique on a par with VSP; the problem is approached in stages. First the Uniwell data are investigated to attempt to remove the tube-wave noise and image the reflector. In conjunction with the Uniwell work, and building on the experience gained from working on it, a new downhole source has been designed which aims to produce less tube-wave energy than the current state of the art sources.

One advantage of VSP is that surveys can be conducted very quickly, with the source on the surface firing at predefined intervals and the receiver array being moved up the borehole. Currently this takes place after the well has been drilled. Occupying a producing well for any amount of time results in lost production which can be very costly. A better solution is to record a VSP or SWI survey while the well is being drilled. This has been investigated by developing a system whereby the data can be processed downhole in real time, with limited up/down communication, to determine the first breaks. The results can then be sent up-hole. The method builds on and supersedes the current state of the art such as Schlumberger's Seismic Vision tool [22].

Finite difference modeling of the new source is performed and compared to a conventional source in a SWI situation, in order to assess the new source design and processing methodology. This modeling was performed using 2D elastic, variable grid, finite difference code, kindly provided by Prof. Thomas Bohlen (University of Kiel). The use of variable grid spacing in the code allows the use of physically realistic sizes for the borehole and receiver arrays. The results of the modeling illustrate the difference between a fluid-coupled source and a clamped source and also highlight the effectiveness of the data processing strategy developed for the new source.

To summarise, the specific contributions to knowledge outlined in this work are:

- Source signature deconvolution for both Uniwell and VSP setups.
- Empirical mode decomposition for tube-wave reduction.
- Design of a novel clamped source, utilising a novel driving method.
- Finite difference modeling and comparison of the new clamped downhole source and the current state of the art fluid-coupled downhole source.

- Investigation of Tube wave suppression devices, using finite difference modeling.

## 1.2 Thesis structure

This chapter introduces the concept of single well imaging and describes the work done in the thesis to improve on the current state of the art. The contribution to current knowledge of the work is set out and the thesis structure is explained.

Chapter 2 details results of the initial literature search, followed by the relevant background theory for the work. It begins with a discussion of wave propagation in a fluid-filled borehole, followed by an in-depth look at tube waves in a borehole. In the next section the current state of the art in downhole seismic sources is discussed with reference to the new magnetostrictive source. The following section introduces empirical mode decomposition, a new method for wave-field decomposition. The chapter concludes with an overview of finite difference modeling.

Chapter 3 introduces the Uniwell experiment, giving an initial overview of the aims of the experiment and explaining the experimental setup and data acquisition. The various data processing stages and the theory behind them are explained. The results section, illustrates the relative success of the different strategies for tube-wave removal. The chapter concludes with an overview of the results and attempts to analyse and explain the relative performance of the various data processing methods used.

Chapter 4 deals with the design, development and construction of the new downhole source. The chapter begins with an introduction to the source and a recapitulation of the relevant background. The stages in the source development are explained starting with the initial prototype testing using a simple fluid-filled borehole model and a piezoelectric sounder, moving on to the deployment of the model in a wave tank, and finally the design and testing of the magnetostrictive source with a presentation of the results of testing in a granite block. The chapter concludes with a discussion of the results and some recommendations for design improvements to the source.

Chapter 5 presents the work done to develop a system for first-break picking in a noisy downhole environment. An overview of the problems and a method to solve them are given. The source signature deconvolution technique is explained for both a VSP and a seismic while

drilling (SWD) setup. This is followed by the results of applying the technique to a VSP data-set, and a discussion of the practical implementation of the system in a real downhole setup.

Chapter 6 details the motivation for and the results of the finite difference modeling of various sources and receiver setups. The key results deal with the comparison of the current state of the art fluid-coupled sources to the new clamped Pseudo random binary sequence (PRBS) driven source detailed on chapter 4.

Chapter 7 concludes the thesis with a recapitulation of the major conclusions from all previous chapters and a discussion of to what extent the initial aims were achieved. A discussion of the limitations and constraints of the work is given, followed by recommendations for further work.

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# Chapter 2

## Background

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### 2.1 Introduction

This chapter presents a review of the relevant literature and a discussion of the relevant theory. It is divided into seven main sections: literature review, waves in a fluid-filled borehole, downhole seismic sources, single well imaging, VSP and seismic while drilling, empirical mode decomposition (EMD) and finite difference modeling.

### 2.2 Literature review

Lamb [43] was the first to predict the types of borehole waves that were later observed in the mid-twentieth century (Sharpe [70] and, Ordning and Redding [58]). These early observations are summarised by White [79]. In the same publication he describes a type of guided wave that travels through the borehole fluid. This can be excited either by a volume displacement, or by a point source in the same hole, or by an incident wave. This is what is described as the tube-wave Schoenberg et al. [66] showed this to be the lowest order trapped mode using guided mode analysis. The fundamental term is the Stoneley mode. Tube wave theory is described in Balch and Lee [3] and qualitatively with examples of real data in Hardage [32]. Tube waves are considered to be unwanted coherent noise by those trying to measure material properties in and around the borehole. They can be at least 30db higher than body wave arrivals [83]. If the first body wave arrivals are obscured by tube waves it is difficult to gain any information about the medium, such as wave velocities, tube waves can also obscure reflections from nearby interfaces, thus rendering survey data almost unusable.

As borehole seismology and its use for oil exploration became more widespread in the late 1980s and early 1990s there was increasing research into how to tackle the problem of tube waves. The methods can be split into two main categories: hardware suppression, i.e insertion of a physical obstruction in the borehole that damps the tube waves, and software suppression which focuses mainly on filtering techniques, such as median, F-K, and wavelet filtering. The

success of the filtering is of course dependent on the quality of the data, the problem being that the data are not always collected with a view to filtering out the tube waves, which due to their low velocity ( $\approx 1500$  m/s) are normally spatially aliased.

Daley and Majer [17], at Lawrence Berkeley National Laboratory (LBNL), in collaboration with the Idaho National Laboratory (formerly the Idaho National Engineering and Environmental Laboratory) and Sandia National Laboratory have developed an inflatable gas bladder that they claim attenuates tube waves by up to 25db [16]. However, at least 30db attenuation is needed in most cases. Mechanically damping the waves in the borehole fluid can only remove some of the tube-wave energy, as Cheng and Toksoz [10], Hardage [32] and West et al. [78] all show that the tube-wave also travels as an interface wave in a small annulus around the borehole, through the formation and the casing. Therefore, even if tube-wave damping is achieved in the fluid, the wave in the formation and casing remains, and can generate new fluid waves when it encounters any sort of impedance change, or washouts.

Chen [9] at Exxon also worked on a similar SWI design. Again it is claimed an inflatable gas filled bladder can reduce tube-wave amplitude by 25dB. However, he admits this is only an estimate and does not show how he arrived at this figure, its is also claimed wall clamping geophones gives another 25dB reduction.

Gal'perin, [29], showed that the amplitude of tube waves recorded by a geophone decreases as the clamping force is increased; however, 25dB is much more than Gal'perin observed. Neither LBNL nor Exxon have been able to explicitly and transparently demonstrate that tube-wave suppression (TWS) devices enable usable data to be collected from SWI surveys. As an example Daley and Majer et al. [17] have been unable to image a salt dome at the Bayou Choctaw site in Louisiana despite numerous surveys.

Software filtering of tube waves would appear to be a favorable approach. It is common practice in exploration to collect data as quickly as possible, and then to process and filter it offline to keep survey costs down. This is especially the case in borehole imaging, as the costs of occupying a well are considerable. Le Wei Mo's and Jerry Harris's [54] approach is to predict the tube waves in a cross well situation, and then subtract them from the data. The problem with this approach is that, firstly, two wells are required, i.e not applicable for single well imaging, and secondly, and more fundamentally, in a single well situation the tube waves will normally overlie the much lower amplitude body waves. Since accurate prediction of the tube-wave

shape is difficult, subtraction generally results in a loss of important body wave information.

Bingwen et al. [6] favour a wavelet filtering approach, referring to previous application of the method to seismic data by Schuster and Sun [69] and Miao and Cheadle [52]. They compare the wavelet transform method against two other common forms of filtering, the median filtering method, and the frequency wavenumber (F-K) filtering method, described by Hardage [32]. The median method attenuates coherent events by the following method: (1) align the data along first break times, (2) apply a median filter along the traces, (3) realign the traces, (4) subtract the result from the original data. This acts like a high-pass filter.

The F-K method computes a 2D Fourier transform of the data, and then uses the fact that events with different velocities occupy different sections of F-K space. If the tube-wave velocity is known, then all events of this velocity can be filtered out. In practice the tube-wave is generally spatially aliased, and therefore is folded back into F-K space, which makes it impossible to remove without removing the body wave data that it overlies. They conclude the only useful method is the wavelet filtering method, and give results of experiments on real data to support this. However, the field of application is a crosswell survey where the tube waves amplitudes are much lower, and there is more separation between the body wave arrivals and the tube-wave arrivals.

Zhang [88] tackles the problem of removing spatially aliased tube waves by using trace interpolation, with a linear step method. This method finds prediction filters from known traces, then estimates missing traces by minimising the prediction error energy. By selecting the zeros of the prediction filters with a neural net, the effects of the aliased data on the prediction filters are removed. The method is applied to real field data. However, the data were initially collected unaliased and later decimated to simulate spacial aliasing. The results show favorable tube-wave removal but the success of this method cannot be determined until it is applied to real aliased data as opposed to a manipulated data set.

Perhaps the most elegant approach is suggested by Schoenberg [68] who demonstrates that in theory tube waves have no energy in the transverse direction, and suggests that if a 3-component record could be orientated in the transverse direction, tube-wave energy would disappear leaving just body wave reflections. See Figure 2.1 for an illustration of the transverse direction. The problem here is knowledge of the original orientation of the receivers and more importantly, knowledge of the receiver sensitivities. Figure 2.1 shows that if the sensitivities

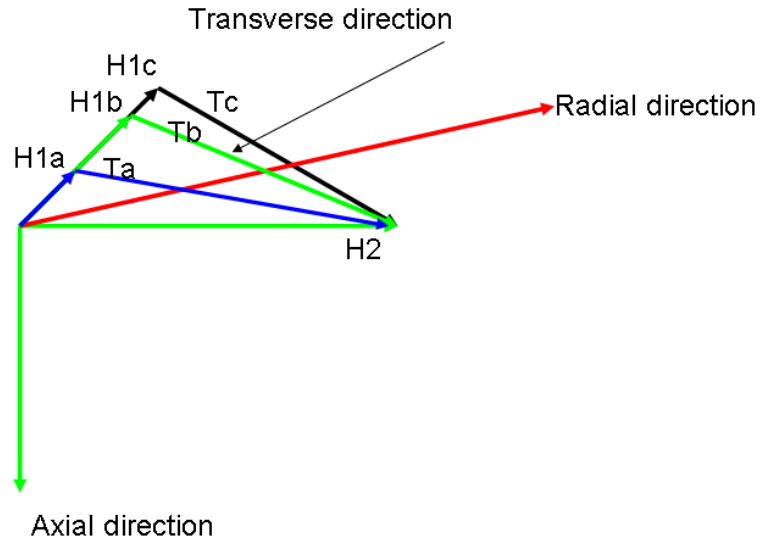


**Figure 2.1:** Diagram showing the vectors associated with a three receiver setup. Subtraction of the horizontal components  $H1$  and  $H2$  yields the transverse component.

of both horizontal components ( $H1a$ ,  $H1b$ ,  $H1c$ ,  $H2$ ) are not equal, subtraction will not yield the transverse direction. Xiao et al. [81] have tried to circumvent the problem by using interferometric imaging where they use a reverse VSP experiment and use reciprocity to replace the shot locations with receiver locations. This results in a pseudo single well imaging survey. However, the method is not well tested and has numerous drawbacks.

To date no-one has been able to demonstrate an effective strategy for eliminating tube waves from a single well imaging record. This is reflected by the fact despite the large amount of research and money spent on developing the SWI technique, it has still not been universally accepted and deployed by any major service or oil company, all of which prefer to rely on the more expensive cross well tomography, 3D VSP and conventional VSP methods.

Since 1998 the University of Edinburgh has been involved in the development of a complete SWI strategy. This started with the Uniwell project, and continued with the work outlined in this thesis. In the Uniwell project a lot was learned about effective sources and the extent of the tube-wave problem. Also a high quality data set was acquired which included both single well and cross well survey data, along with a separate airgun record which could be used to orientate the receivers.

## 2.3 Waves in a fluid-filled borehole

When measurements are made inside a fluid-filled borehole, the first records will usually be body waves from the source, traveling along the interface between the borehole and the surroundings, or tube waves traveling either in the fluid or along the interface. It is very important to know whether these body waveforms recorded with a wall locking geophone are the same as what would be recorded in the absence of the hole. In the case where the waveforms are different, it would be impossible to correlate the downhole data with surface data without knowledge of the effects of the borehole. Balch & Lee [3] address this problem by solution of the classical wave equation.

When the radius of the borehole is very small compared to the wavelength the dispersion relation in the borehole reduces to:

$$C_T \hat{=} \frac{\omega}{k_0} = \left( \frac{1}{\alpha_1^2} + \frac{\rho_1}{\rho_2 \beta_1^2} \right)^{-1/2} \quad (2.1)$$

Where  $\alpha_1$  and  $\beta_1$  are the respective P-wave and S-wave velocities in the surrounding medium,  $\rho_1$  and  $\rho_2$  are the respective densities of the borehole fluid and the medium. This phase velocity is essentially the tube-wave velocity, determined by White [79].

Balch and Lee [3] describe the effect of the borehole on the axial displacement, for general parameters and a frequency range of 25Hz to 300Hz. Their results show that when the borehole radius is small compared to the wavelength of the signal, the ratio of the axial motion in the borehole to the ratio of axial motion in the absence of the borehole is close to one. Since this bandwidth is approximately the bandwidth of interest in SWI, it can be concluded in the case of signals arriving from outside the borehole the borehole itself has no effect on the data recorded in the axial direction.

## 2.4 Tube waves

The term tube-wave is given to a generally high amplitude coherent noise event that is observed during seismic experiments when the receiver, the source, or both, are located in a fluid-filled borehole. White [79] presented a thorough quantitative study of tube-wave theory. He derives a wave equation describing the axial motion of a fluid column in a thick walled tube:

$$\frac{\partial^2 u_z}{\partial z^2} = \left[ \rho \left( \frac{1}{B} + \frac{1}{M} \right) \right] \frac{\partial^2 u_z}{\partial t^2} \quad (2.2)$$

where  $\rho$  is the density of the fluid,  $B$  is the bulk modulus, and  $M$  is  $Eh/2b$ , where  $E$  is Young's Modulus,  $h$  is the thickness of the tube and  $b$  is the radius of the tube. Equation 2.2 shows that a fluid column in a thick walled tube is capable of supporting pulses of any waveform  $f(t - z/c_T)$  or  $g(t + z/c_T)$ , traveling in either direction, without dispersion or attenuation. This establishes a key characteristic of tube waves. Which is that they are essentially non-dispersive. Therefore their shape should stay essentially the same as they propagate away from the source. If the tube-wave shape can be estimated, the tube-wave can be subtracted from every shot record to leave the body wave.

Schoenberg et al. [66] analyse the dispersion characteristics of propagating modes in more detail. They conclude that all propagating modes in a fluid-filled borehole have an exponentially decaying spatial dependence in the outer formation. This leads us to another observation that the tube-wave magnitude is lower in the outer formation than in the well-bore fluid. Therefore the tube-wave magnitude recorded with a clamped geophone is inversely related to the clamping force of the tool. The greater the clamping force, the more the geophone follows the motion of the formation as opposed to the fluid. This was observed qualitatively by Gal'perin [29, pg. 21].

In the second part of the same paper, Schoenberg et al. [67] described how they built scale models of a cased and uncased borehole, and used them in the laboratory, to investigate the theory derived in part one. Data recorded in the cased hole model illustrate the tube-wave problem, Figure 2.2. Another important point made in this paper, is that accurate measurement of the modal dispersion, and adequate modal separation, can only be achieved with frequent spatial sampling, for example, for a tube-wave of peak frequency 400Hz, the spacing between receivers, needs to be of the order of 1m to prevent spatial aliasing. Such close spacing of receivers is unusual in VSP, or single well imaging, and as a result, in almost all cases tube waves are spatially aliased in the data. This means they cannot be removed in the F-K domain without severely attenuating body waves, illustrating the fact that in order to combat tube waves, more needs to be known about their behaviour, in particular their particle motion.

This subject is covered by Cheng and Toksoz [10], with regard to a sonic logging application, although most of their analysis applies to the higher frequency sonic logging situation. Their

results for the particle displacement of a propagating tube-wave can be seen in the curves plotted in Figure 2.3. These curves show that the size of the particle displacement orbit in the fluid column is much larger than that in the surrounding formation, a result derived by Schoenberg et al. [67] in an earlier paper. It follows that the radial component of tube-wave motion is smaller than the axial component.

Schoenberg [68] addressed the problem of the interaction of an arbitrary plane wave with a fluid filled borehole. His analysis is formulated for three-axis, full waveform, borehole seismic data. This makes it a good resource for understanding the data collected in the Uniwell experiment. He analyzes a situation of particular relevance to this work, i.e the particle velocity in a fluid-filled borehole due to an incident P-wave:

$$v_r = \frac{i\Omega_L r}{2r_b} \frac{c_T^2}{\gamma\alpha_f^2} \frac{(1-2\gamma\cos^2\delta)[1-(\alpha_f/\alpha^2)\cos^2\alpha]}{1-(c_t/\alpha)^2\cos^2\delta} + \cos\theta\sin\delta + \frac{i\Omega_L r \cos 2\theta}{(1-\gamma)r_b} \sin^2\delta \quad (2.3)$$

$$v_\theta = -\sin\theta\sin\delta - \frac{i\Omega_L r \sin 2\theta}{(1-\gamma)r_b} \sin^2\delta \quad (2.4)$$

$$v_z = \frac{c_T^2}{\beta^2} \frac{\cos\delta(1-2\gamma\cos^2\delta)}{1-(\frac{c_T}{\alpha})^2\cos^2\delta} + \frac{i\Omega_L r \cos\theta}{r_b} \cos\delta\sin\delta \quad (2.5)$$

Where  $\Omega = \frac{\omega r_b}{\beta}$ ,  $\omega$  is radial frequency,  $r_b$  is borehole radius, and  $\beta$  is shear speed in the formation.  $\alpha_f$  is the compressional speed in the fluid,  $c_t$  is the tube-wave speed,  $\gamma$  is the ratio of shear wave velocity to compressional velocity in the medium and  $\delta$  is the angle of incidence of the P-wave relative to the vertical axis of the borehole.

The case where  $\delta = 0$  (i.e a wave traveling parallel to a vertical borehole) is of interest. Equations 2.3 to 2.5 show that in this case there is only axi-symmetric motion in  $v_r$  and  $v_z$  with  $v_\theta \equiv 0$ . This suggests that there is no tube-wave component in the tangential or transverse direction, therefore if the tangential direction can be determined, it should contain only reflected body waves from outside the vertical plain of the borehole and random noise. We note that direct waves from the source will not be visible in the tangential direction. However, the crosswell data does contain reflections from a dipping interface. It was hoped that these reflections might be visible if the data was transformed to the tangential direction.

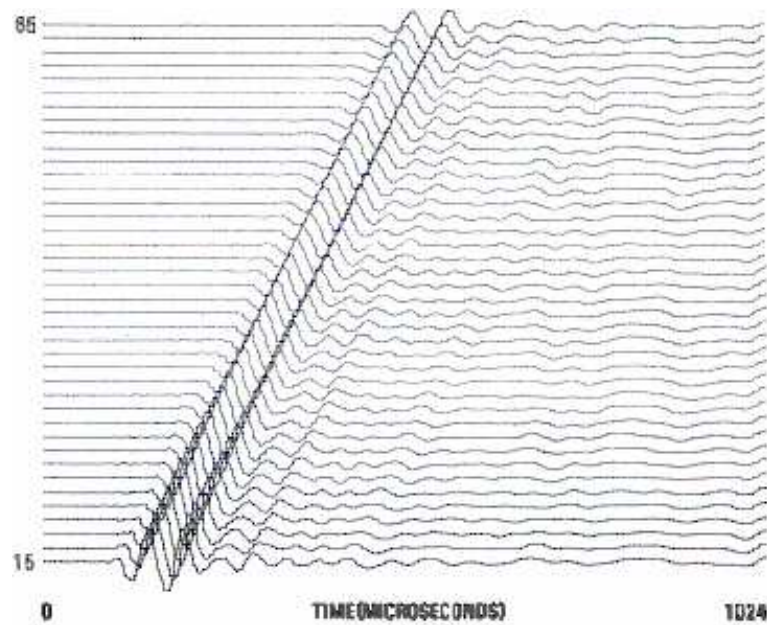


**Figure 2.2:** Data recorded in a model of a cased borehole showing only tube-wave arrivals.

The axes of horizontal geophones are oriented at 45 relative to each other. Therefore the transverse direction could be obtained by subtraction of the horizontal components on every sonde. This could be performed either before or after the source signature deconvolution step.

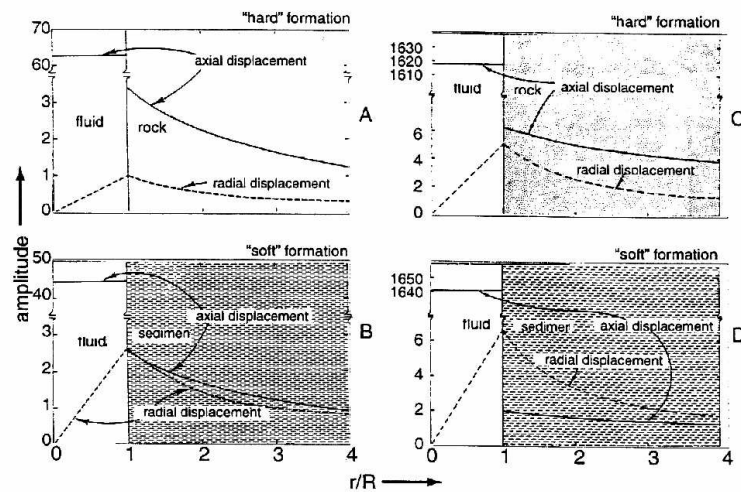


**Figure 2.3:** Plots showing axial and radial particle displacements created by VSP tube waves, for boreholes penetrating a hard formation and soft sediment.  $R$  is the borehole radius. Only a single frequency is analysed in each plot, viz., (A): 409Hz, (B): 427Hz, (C): 82 Hz, (D): 74 Hz. Taken from Hardage [32]

## 2.5 Single well imaging including Downhole sources

Tube wave noise in SWI surveys, can be reduced by using an informed choice of downhole source. Since tube waves are created by volume displacement in the fluid column of the borehole, a source that transmits little or no energy to the fluid is favourable. However, all of the current state of the art sources are fluid-coupled. One reason for this is speed of deployment. Oilfield service companies aim to complete their surveys in the minimum time possible. A clamped downhole source slows operations down due to the fact it needs to be clamped and unclamped at every shot point. There are also concerns about the risk of the tool becoming stuck in the hole, or in the case of a seismic while drilling operation, being damaged by the high velocity circulating drill mud. A discussion of the fluid-coupled source used in the Uniwell experiment follows below.

The Orbital vibrator source (OVS) was developed by Conoco in the 1980s to generate shear waves in a fluid filled borehole, without direct mechanical coupling to the borehole wall Cole [13] summarizes the history of the source. Production was licensed to OYO Geospace, who redesigned and marketed the source as an effective S (shear) and P (compressional) wave source. There are three types of OVS: single and dual motor mechanical source and a solid-state piezo-electric source (POVS). The mechanical type operates by driving two eccentric rotating masses around the source axis, they are encased in a cylindrical housing that is suspended in the borehole fluid as shown in Figures 2.4, and Figure 2.5. The centrifugal forces induced by the rotation of the eccentric masses move the whole source in the radial direction of the borehole. This results in omni-directional energy being transmitted to the formation through fluid coupling between the source and the borehole wall. The resulting waves have the same primary frequency as the spin frequency of the source; this can be up to 400 Hz. The same effect can be accomplished using a phased array of piezoelectric sources arranged around the borehole axis. The piezoelectric type can generate waves above 4 kHz.

Advocates of the OVS claim that it generates nominal tube-wave energy [75]. This is in direct contradiction with results from field surveys, where it has been shown that tube waves are at least 30 dB higher than body waves. An additional problem with this theory is that, as a volume displacement source, it transmits all its energy to the fluid and then relies on fluid coupling to get this energy into the formation. The transfer is obviously not 100% efficient, and a lot of energy remains in the fluid, which is observed as tube waves. Nakagawa, Daley and Majer [56] show that source eccentricity can also result in high tube-wave amplitudes.

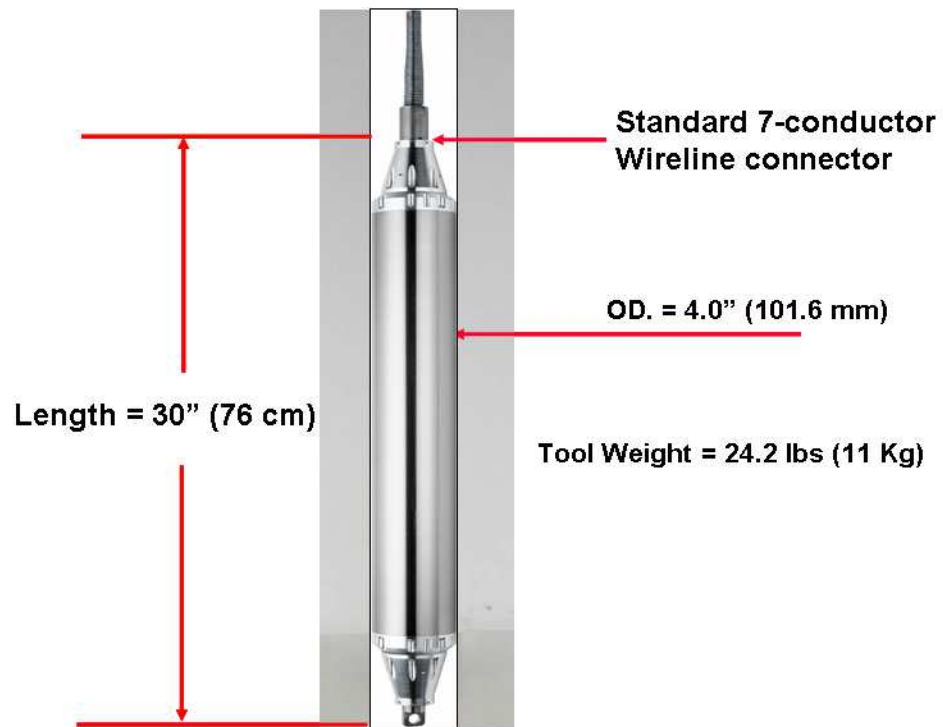


**Figure 2.4:** Photograph of a dual motor orbital vibrator source, with weight and dimensions.

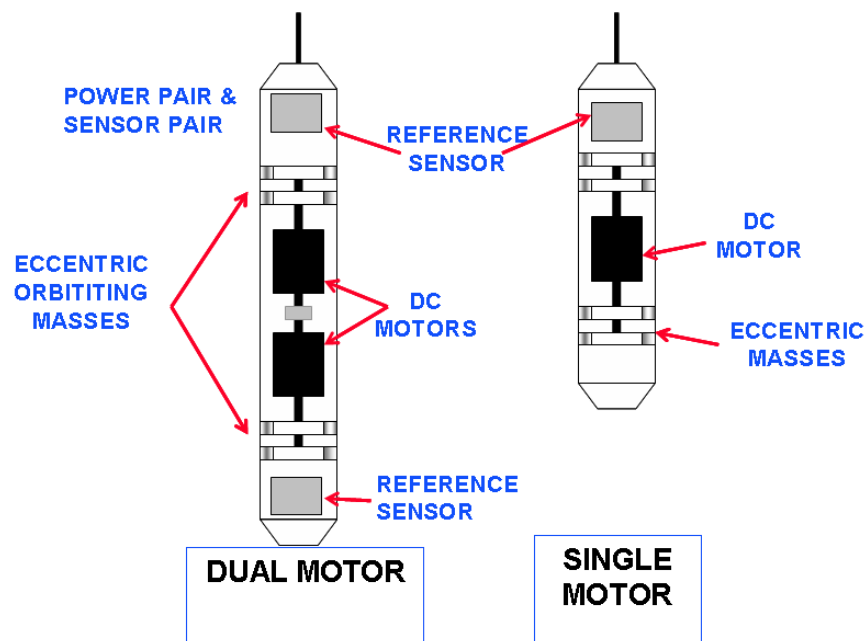


**Figure 2.5:** Schematic diagram of dual and single motor orbital vibrator source, showing eccentric masses and reference sensors.

Recently a lot of work has gone into characterizing the OVS and the type of waves it generates. Leary and Walter [44] describe the OVS as a linear-physics rotating point force model with effective mechanical dimension less than or equal to the diameter of most boreholes (100mm). Walter and Leary [75] also use crosswell seismic data to show that OVS P-wave radiation from a borehole can be described by diffraction and borehole wall conversion of the OVS acoustic wave. However, they insist that there is little residual energy in the axial pressure field and therefore OVS tube waves are very low amplitude compared with other borehole sources. This is slightly misleading since, while it may be true that in comparison with airguns the OVS tube waves are low amplitude, they are still at least 30dB above the body waves and therefore a major problem.

Nakagawa and Daley [55] use a series solution in the frequency-wavenumber domain to examine the waves generated by the OVS. They conclude that in theory the OVS should produce low amplitude tube waves. However, due to off-centre source placement, these waves are in practice much higher in amplitude than expected. They also demonstrate the conventional OVS (rotating dipole source) can be generalised to higher order multipole sources, and that the off-centre OVS is essentially a superposition of these multipole sources.

One of the most promising sources is built around a magnetostrictive actuator. Magnetostrictive materials exhibit a change in length when subjected to a magnetic field. There are many different types of such materials, but the one which exhibits the greatest change in length for a given magnetic field is an alloy of terbium, dysprosium and iron, trade named Terfanol-D. Terfanol-D exhibits strains of 1000 to 2000 ppm, reaching over 0.1% linear motion. Displacement of the rod is proportional to its length, a 50mm rod will easily provide  $50\mu m$  displacement and designs are available with displacements up to  $110\mu m$ . Sandia Laboratories were one of the first to build a downhole source around a magnetostrictive actuator [14]. The source was devised as a reaction mass shear wave generator. It consisted of an actuator with contained a Terfanol-D rod. However, Sandia's design utilised a large reaction mass which put a lot of stress on the Terfanol-D rod, which is very brittle under shear stresses. The test setup they used is shown in Figure 2.6. This resulted in the source being difficult and unreliable to deploy. Since Sandia's initial testing phase, there has been no published research into using a Terfanol-D actuator. The major stumbling block has always been the driving method, it is simply not possible to drive this source with a lot of power, due to the resonance problem which results in damage to the Terfanol-D rod.

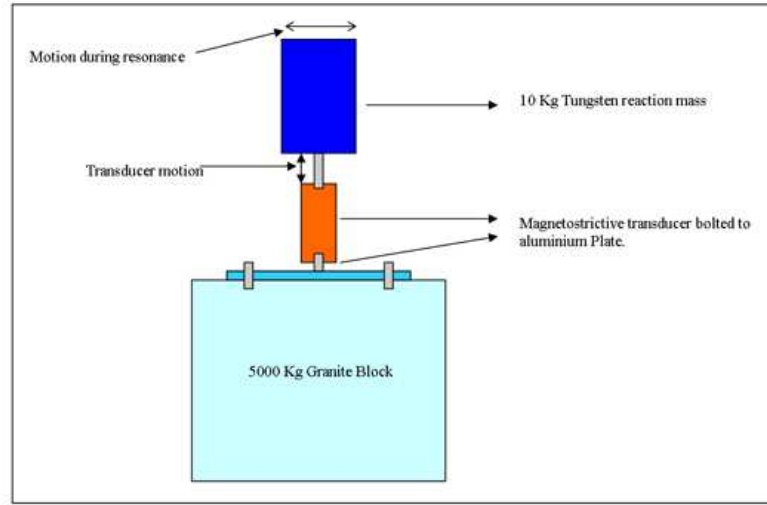


**Figure 2.6:** *Test setup for the reaction mass driven magnetostrictive source.*

A new design for the source was developed, in cooperation with colleagues, which utilises a hydraulic amplifier design and a low power coded waveform driving method, exploiting the time-bandwidth product to extract the signal from the noise.

## 2.6 Empirical Mode Decomposition (EMD)

Empirical mode decomposition [33] is a deterministic time domain technique for the adaptive decomposition of signals into oscillating components with a local zero mean, known as Intrinsic Mode Functions, (IMF). The technique can be compared to a time-varying filter bank, which consists of a series of time limited, bandpass filters with bandwidths that vary with time. The main appeal of EMD as a tool for analyzing seismic data is that it does not rely on any basis functions or predetermined filters: it is completely data driven and therefore deterministic. The major limitation of the method is the possibility that only a small number of the IMFs fall within the frequency range of interest, which is 0-200Hz in the case of the Uniwell data.

Given a signal  $s(t)$ , the algorithm works by initially identifying all extrema of  $s(t)$ , and interpolating between the minima, and the maxima to end up with two respective envelope functions. The mean of the two envelopes is  $m(t)$ , subtraction of this mean from  $x(t)$  yields

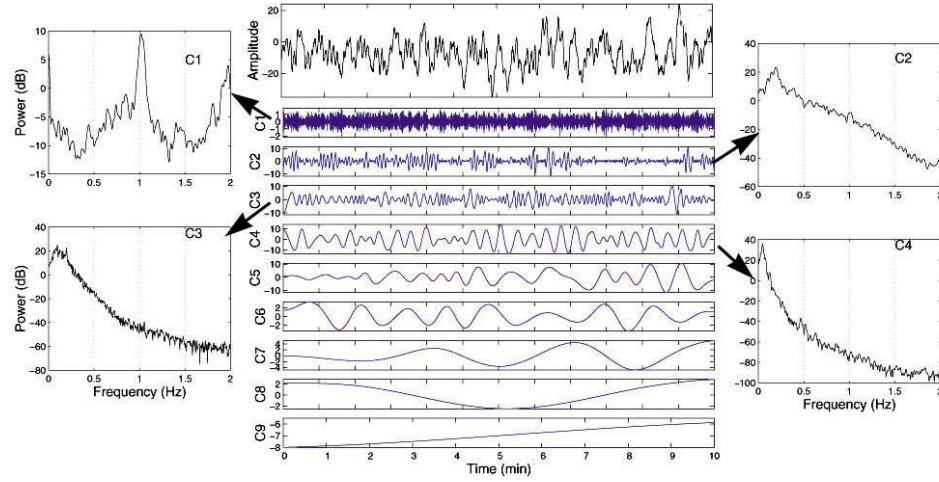


**Figure 2.7:** Middle panel: Empirical mode decomposition of a typical EGG recording (top) into nine components (C1 to C9), each with clear physical meaning. Left and right panels: the power spectra of the first four components. The peak frequencies of components C1 to C4 are successively 1.02 Hz, 0.2 Hz, 0.1 Hz and 0.05 Hz, which correspond to the heartbeat, respiratory artefact, harmonic signal and gastric slow wave, respectively.

the first IMF  $d(t)$ . The procedure is then iterated on the residual. In practice it is necessary to iterate the steps to obtain  $d(t)$  until it can be considered to have zero-mean according to some stopping criterion. The residual is then computed and the process is repeated to form the next IMF, and so on. This iterative procedure is known as sifting. Since the number of extrema is decreased when going from one residual to the next, the decomposition will always be completed with a finite number of modes. Appendix C contains the complete algorithm and the result of applying the technique to marine VSP data.

An example of the decomposition of an EGG is shown in Figure 2.7. Here the IMFs have a clear physical meaning, corresponding to the heartbeat, respiratory artefact, harmonic signal and gastric slow wave. As can be seen from this example, the technique is very useful in fields such as medicine. However, it is more difficult to infer a physical meaning to the IMFs when analyzing seismic data.

## 2.7 Finite difference modeling

The Finite difference time domain (FDTD) technique is one of the most widely used methods to simulate wave propagation in 2-D and 3-D elastic media with fairly general variations in

spatial elastic properties. The very first synthetic seismogram created by FDTD were produced by J.T Cherry [12] to aid in detection of underground nuclear tests. The first application of this method for exploration came from Kelly, Ward and Treitel [37] who introduced the method as an interpretative aid giving several models of exploration interest. They also discuss implementation aspects such as grid dispersion, artificial edge reflections, and the choice of spatial and temporal sampling increments.

Virieux [74] took the technique a step further with the introduction of the staggered grid formulation. His work was based on a FDTD scheme first devised by Madariaga [48] to model crack propagation. The velocity and stress components are located on a staggered grid with velocity being located half a time step away from stress. This means that the model can handle a fluid-solid interface where Poisson's ratio goes to zero. Virieux's scheme [73][74] was based on the first-order coupled elastic equations of motion and constitutive laws expressed in particle velocities and stresses. His operators were 2nd order accurate in space and time. Levander (1988) extended this scheme to 2nd order accuracy in time and 4th order in space; he concludes the scheme can be used to accurately model P/SV wave propagation in a variety of media with varying Poisson's ratios, making it ideal for modeling marine problems.

It is this characteristic which also makes the FDTD scheme ideal for modeling wave propagation in fluid filled boreholes. Yoon and McMechan [82] demonstrated this by 3-D FDTD modeling of elastic waves in borehole environments. Their treatment is asymmetrical and based on a Cartesian coordinate system. Due to the asymmetry, they demonstrate accurate modeling of features such as washouts, cement, mud invaded zones, tools in the hole and arbitrary lithological variations. However, they were modeling a high frequency ( $\approx$ kHz) sonic logging survey with 50mm grid spacing. The small grid spacing used here is very computationally expensive (run lengths were in the range of days on a large supercomputer) despite the fact that they were only modeling the immediate area around the borehole.

However, in SWI the area of interest may extend to distances greater than 100m around the borehole. This means that a grid spacing of 50mm would require an inordinate amount of memory (in the 100s of Gb range), and would be extremely inefficient due to oversampling the area outside the borehole.

The solution is to use a variable grid spacing for the finite difference stencil, whereby the immediate area of the borehole is discretised using a very small grid spacing, at the centimeters scale, and the rest of the model uses a very large grid spacing. The problem in practice is handling the behaviour of the code at the boundary between coarse and fine grids, so that the waves pass from one region to the next without any artificial reflections .

One solution to the variable grid problem is based around grid stretching. Jastram and Tessmer [36] describe a FDTD modeling experiment on a grid with vertically varying spacing. They use this to accurately model a region with very different material properties, such as a site with a large weathering layer resulting in large velocity contrasts. They extend this method to the 3-D modeling of elastic waves in a borehole, including generation and scattering of tube waves using a mapping function to change the horizontal grid spacing [25]. Their results show that when modeling a cross-well borehole survey where the diameter of the borehole is not small compared to the wavelength of the signal, it is essential to explicitly include the boreholes in the model in order to accurately interpret cross well recordings. This is due to the complex phenomenon of wave scattering due to the presence of the boreholes and the strong events related to tube-wave generation and scattering in the source and receiver wells.

Wu, Harris and Franklin [80] build on this by presenting a single well modeling example with the added flexibility of a viscoelastic treatment. Instead of starting with the elastic wave equation, they use the viscoelastic equations which permit the representation of attenuating layers such as mud cakes. They use a smoothly varying function to change the grid spacing from coarse in the formation to fine in the vicinity of the borehole. By smoothly varying the spacing they claim to avoid artificial reflections generated by the grid transition. The horizontal grid spacing varies from 0.01m to 0.26m over a 0.36m transition region; the spacing in the vertical direction is 0.27m throughout the grid. Their technique allows accurate modeling of complex wave scattering effects near the borehole and reflections from bodies such as salt flanks that may be up to 60m away.

In spite of the computational efficiency of the grid stretching method, it still requires considerable computing power to accurately model a single well imaging survey. This means the code needs to be run on parallel machines. Bohlen [8] demonstrates parallel finite difference modeling in 3-D employing the message passing interface (MPI) to run the code on a cluster of Linux machines and a Cray T3E, concluding that as the grid size increases the performance of the Linux cluster decreases, due to the relatively slow ethernet, whereas the performance of the supercomputer stays constant right up to very large grid sizes. Better performance, with much faster time steps, was obtained when running the code on a Linux cluster made up of dual processor Dell Xeon PCs. This seems to be due to the relatively fast CPUs on these PCs. For smaller models the performance is excellent up to 32 CPUs, when MPI overheads start to level out parallel gains.

The spatial adaptation of the finite difference grid relative to the material parameters leads to significant savings in computation time, and allows modeling of both small scale features and large scale structures such as boreholes and reservoir layers, respectively. The initial work was done using code based on Jastram and Belle's [35] scheme, as adapted by Falk [27]. These results suffered from high frequency instabilities. At the time this was thought to be due to dispersion and poor choice of interpolation operators at the grid boundaries. Recently Khn and Bohlen [40] have shown that these instabilities are due to non-causal integration of fine grid points at the boundary. They modified the FD operators to integrate these points in a causal manner. Their new scheme is called ACFGT, asymmetric coarse to fine grid transition. The final results presented here were generated using this ACFGT finite difference scheme. The code uses an open source implementation of MPI to run over a cluster of Linux PCs.

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## Chapter 3

# The Uniwell experiment data analysis and conclusions

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### 3.1 Introduction

The Uniwell experiment [87] - conducted at the Humble test site, Texas - was designed and executed in order to assess the viability and effectiveness of the single well imaging technique. The experimental setup consisted of three wells as shown in Figure 3.1: an Oyo Geospace orbital vibrator source and an Amoco 5-level 3 component geophone string, deployed in COG 54, an airgun source was deployed in COG 30; GEO 1 contained cemented geophones at 50ft intervals. One of the aims of the experiment was to investigate whether body waves or reflections could be identified in the single well imaging set up. The result of the initial data processing showed only tube-wave arrivals on the single well recordings, and body wave and tube-wave arrivals on the cemented geophones in GEO 1.

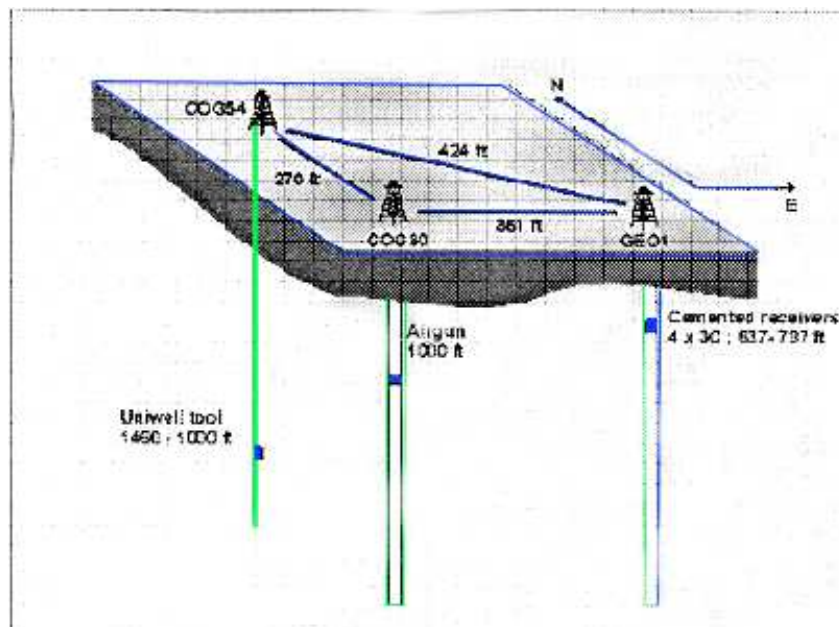


**Figure 3.1:** The experimental setup for the Uniwell test. [87]

The setup made it possible to estimate the tube-wave to body wave ratio, performed as follows [83]. The airgun source was used to calibrate the cemented phones relative to the Uniwell sondes. This was done by firing the airgun and observing the amplitude of the direct arrivals on both the Uniwell sondes and the cemented phones. After a spherical divergence correction the ratio of the direct arrivals, on the two different sensors was computed. At this point the OVS source was spun in the Uniwell hole, allowing tube-wave and body wave arrivals to be isolated on the Uniwell geophones and cemented geophones respectively. The r.m.s amplitudes of these arrivals were estimated over a chosen time window for all three components on both phones. After correcting for spherical divergence and multiplying by the sensitivity ratio (previously determined using the airgun shots), the body wave amplitude from the cemented phones was compared to the tube-wave amplitude of the Uniwell phones. The resulting ratio was about 23dB.

This chapter details the work done to reprocess the data in an attempt to uncover the body waves. Three main approaches are followed: rotation of the horizontal components into the tangential or transverse direction; deconvolution using the tube-wave reflection; and empirical mode decomposition. All of these approaches use source signature deconvolution as the first step.

The chapter is structured as follows. The initial data processing work is described and some basic conclusions are reached about the data. These support the choice of source signature deconvolution as the next step. The method and theory for the source signature deconvolution is then presented, followed by the results for the initial deconvolution. The next section describes the attempts to uncover the body waves and presents the results of the rotation, tube-wave deconvolution and EMD methods. Finally, the limitations and contributions are discussed in the conclusions section along with the motivation for the next stage of the project.

## **3.2 Experimental setup**

The experiment took place at the Humble Test Site, near Houston, Texas, in November 1998. [87]. Three wells were used as shown in Figure 3.1. The Uniwell test tool located in COG 54, consisted of a single fibre-optic wireline, with the following components, top down as shown in Figure 3.2:

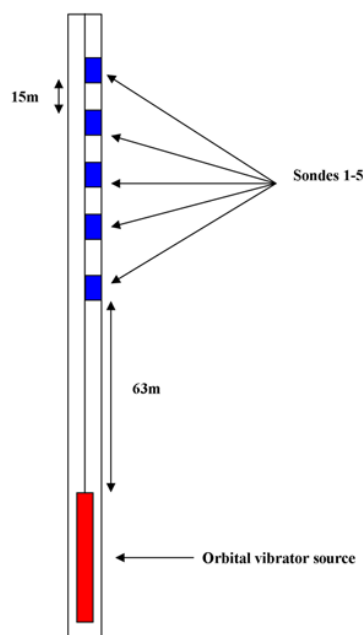


**Figure 3.2:** Sketch of Uniwell tool string as deployed in COG 54.

- 1 Telemetry interface unit
- 5 Amoco sondes at 15m (50ft) intervals, three components per sonde, which were numbered 1-5 top to bottom
- 1 digitizer, 7.5m (25ft) below sonde 3
- 1 Oyo orbital source 63m (210ft) below sonde 5

GEO 1 contained cemented three component geophones. These were used for the crosswell study and for determining tube-wave to body-wave ratio. An airgun source was located in COG 30 at a fixed depth of 1,000ft.

### 3.2.1 Data Acquisition

The Uniwell tool was lowered into COG 54 to a header depth of 2000 ft (depth of sonde 1); this put the source at 2410ft. Each sonde was clamped to the borehole wall using an inflatable bladder. Once clamped, four successive sweeps were made with the orbital vibrator source. The record length was 12 seconds, with the sweep length about 12 seconds. The source was

rotated up to a peak frequency of 200Hz and then allowed to sweep down under friction. The source signature for each shot was recorded by a horizontal geophone, fixed to the casing of the source. The Uniwell tool was then unclamped and moved up the well by 10ft. The whole process was repeated at intervals of 10 ft up to a header depth of 1000ft.

Unfortunately since an accelerometer was not used to measure the source signature, there will be an unknown phase shift in the source signature in the far-field, this could have affected the deconvolution results.

The recordings were of 12 seconds duration sampled at 0.5 ms on a DAS recorder, with 3-500 Hz recording filters. The Uniwell data were digitized downhole and transmitted up the fibre optic wireline to the recorder.

The airgun source was being deployed in COG 30 as the acquisition was continuing in COG 54. When the Uniwell tool reached a header depth of 1460 ft, the airgun source was ready. Four short (1s) records were made with the airgun source for every level of the Uniwell tool. Using these shot records the orientation of the Uniwell tool can be determined for header depths 1,460 - 1000ft. This is useful since the tool can twist as it is unclamped and pulled up, so the orientation may be different for every shot. The airgun records also allowed the Uniwell geophones to be calibrated relative to the cemented geophones in GEO 1.

### **3.3 Initial data processing**

The original data were recorded in SEG-D format which meant that all 28 channels for one shot were contained in the same file. In order to work with the data, they first had to be converted to ASCII format. Once the data were in ASCII it was straightforward to write a program to extract the channels into separate files. The source signature was recorded on channel 28 for every shot. Figure 3.3 shows a single sweep of the source as measured with the source monitor geophone and Figure 3.4 shows its amplitude spectrum. Looking at these plots it is obvious that the output energy is frequency dependent.

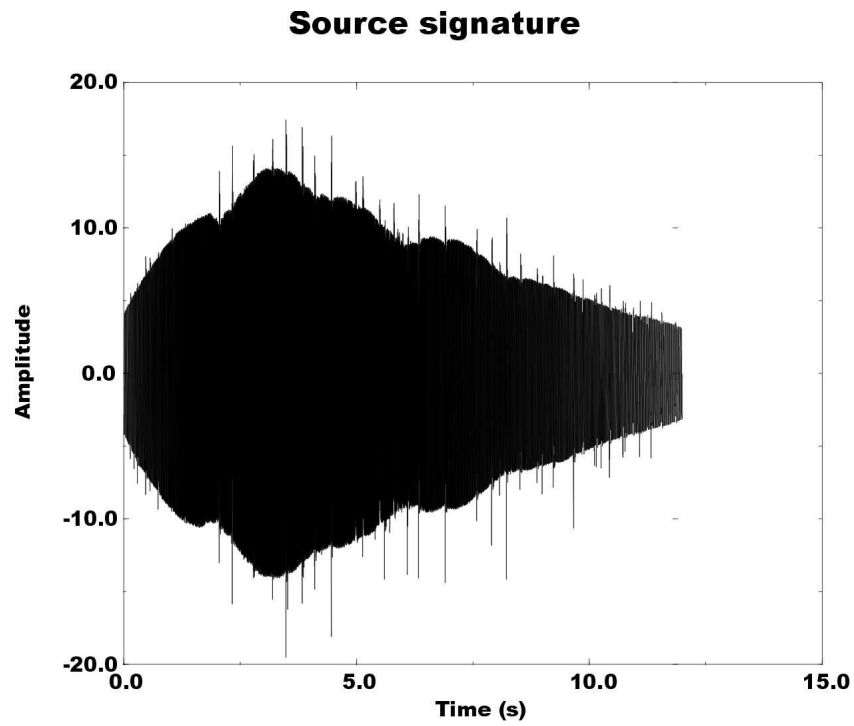


**Figure 3.3:** *Orbital vibrator source signature.*

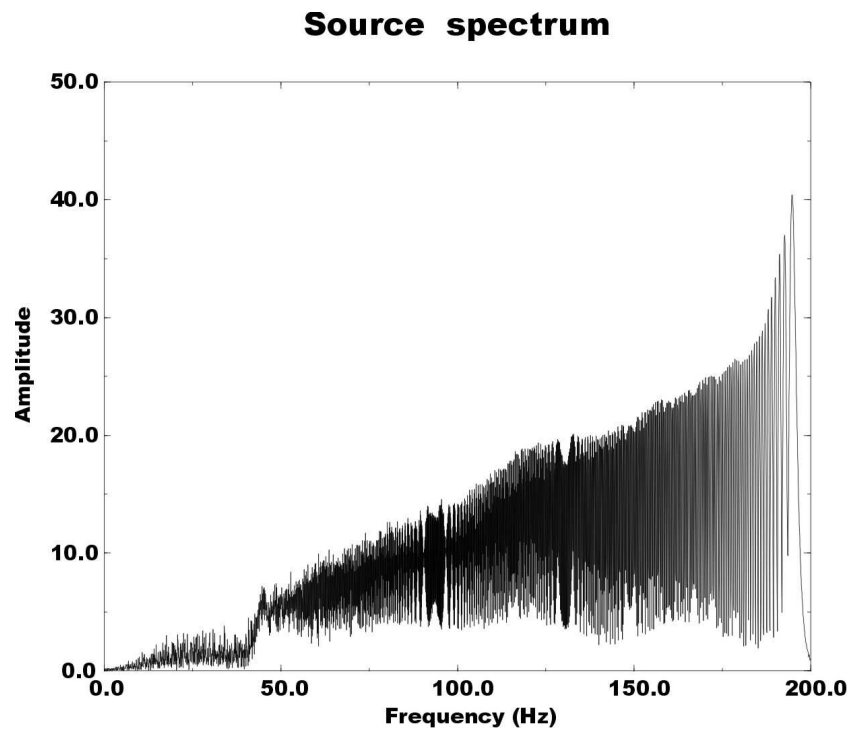


**Figure 3.4:** *Orbital vibrator source spectrum.*

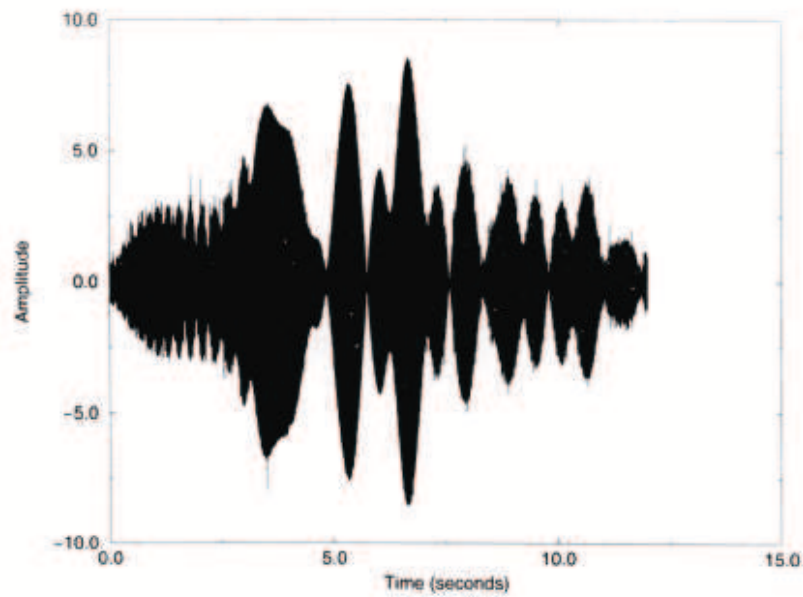


**Figure 3.5:** *Time domain result of stacking four consecutive sweeps, measured by the source monitor on the tool. From Ziolkowski et al. [87].*

Ziolkowski et al. [87] demonstrated that the source signature is not repeatable from shot to shot. This is illustrated in the following Figures: Figure 3.5 is the result of stacking four consecutive shots in the time domain, and Figure 3.6 is the same stack in the frequency domain. Figure 3.8 is cross correlation of the stack with the single sweep of Figure 3.3. This looks nothing like the auto-correlation of the single sweep as shown in Figure 3.7, it is obvious that cross correlation after stack would result in very poor data quality. Even the auto-correlation function of the single sweep in Figure 3.7 is not an ideal wavelet: it has large side-lobes, and has a very ringy character.

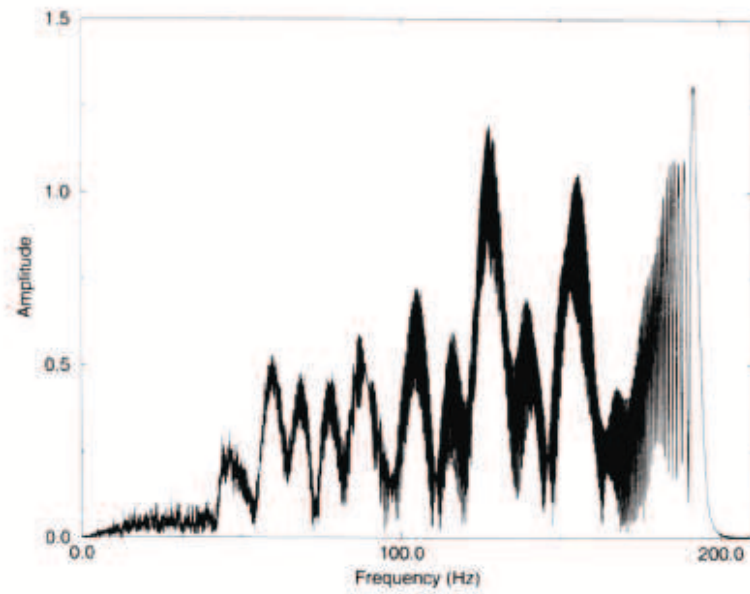


**Figure 3.6:** *Frequency domain result of stacking four consecutive sweeps, measured by the source monitor on the tool. From Ziolkowski et al. [87].*

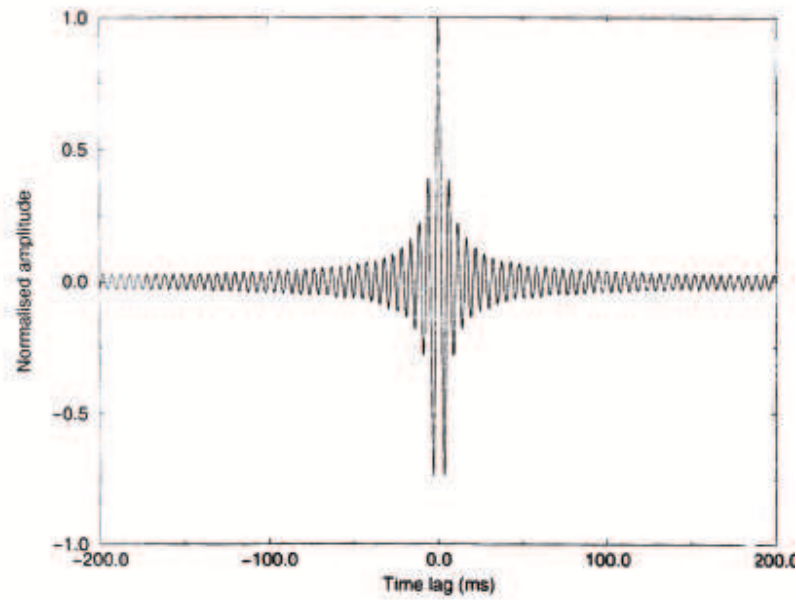


**Figure 3.7:** *The result of the auto-correlation of the measured source signature sweep. From Ziolkowski et al. [87]*

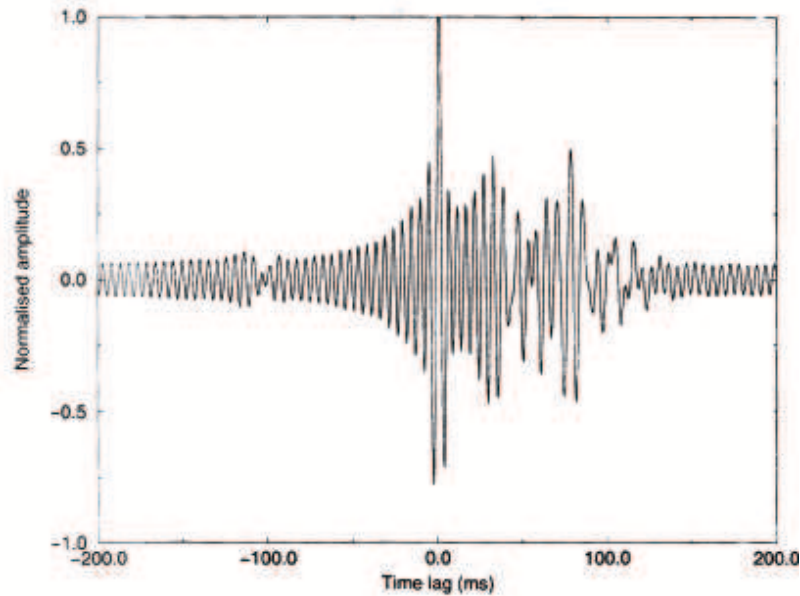


**Figure 3.8:** *The result of the cross-correlation of the stack shown in Figure 3.5 and the source sweep. From Ziolkowski et al. [87]*

Clearly the conventional processing sequence of stacking followed by cross-correlation with the sweep is not suitable for this source. The more logical alternative is signature deconvolution, made possible by the fact that the source signature is measured and recorded for every sweep, using a horizontal geophone mounted on the source housing.

### 3.4 Signature deconvolution

The aim of the signature deconvolution is to take the long record in Figure 3.9 and convert into a shorter higher resolution trace that is easier to process and interpret. This is achieved by converting the source wavelet - which is present in all the data for that shot - to a zero phase wavelet. Zero phase is chosen since it is the best approximation to a delta function, i.e an ideal spike source, and is the shortest possible wavelet within a given bandwidth [5]. The filter which converts the source signature to the zero phase wavelet is convolved with the data recorded for that sweep. Any noise could be attenuated later by stacking.

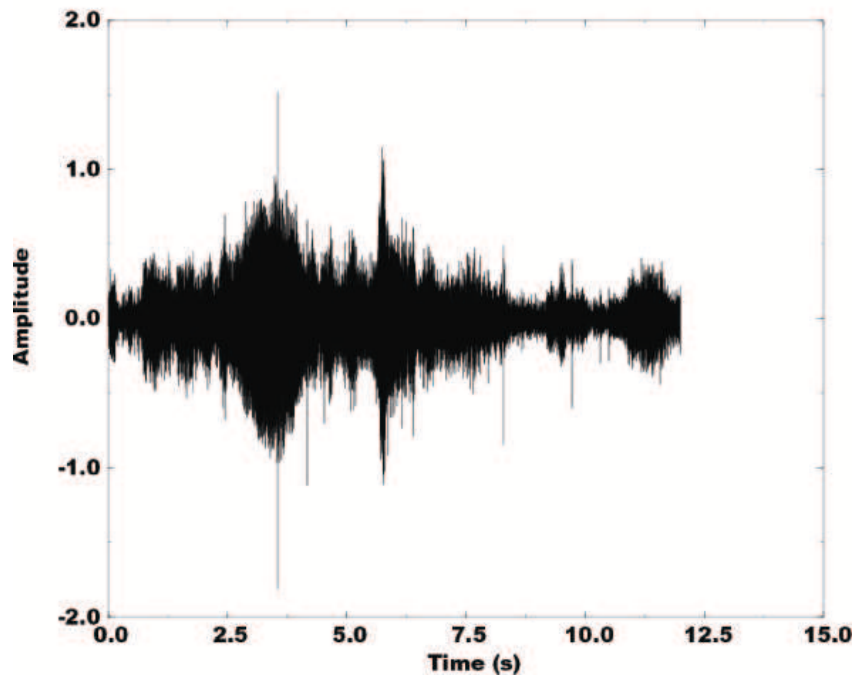


**Figure 3.9:** *An example of a shot record before any deconvolution.*

Figure 3.10 shows the amplitude spectrum of the chosen zero-phase wavelet, which is a smoother version of the spectrum of the source. The zero phase wavelet that has this amplitude spectrum is shown in Figure 3.11. This is the wavelet that formed the basis of the signature deconvolution. It was important to try to make it as sharp as possible with minimum side lobes, as large side lobes will cause ringing in the data. It appears that the smoother the spectrum the smaller the side lobes. Any sharp changes in slope in the frequency domain translate into large side lobes and ringing in the time domain. The gain in resolution produced by this method as opposed to auto-correlation can be seen by comparing Figure 3.11 with Figure 3.7.

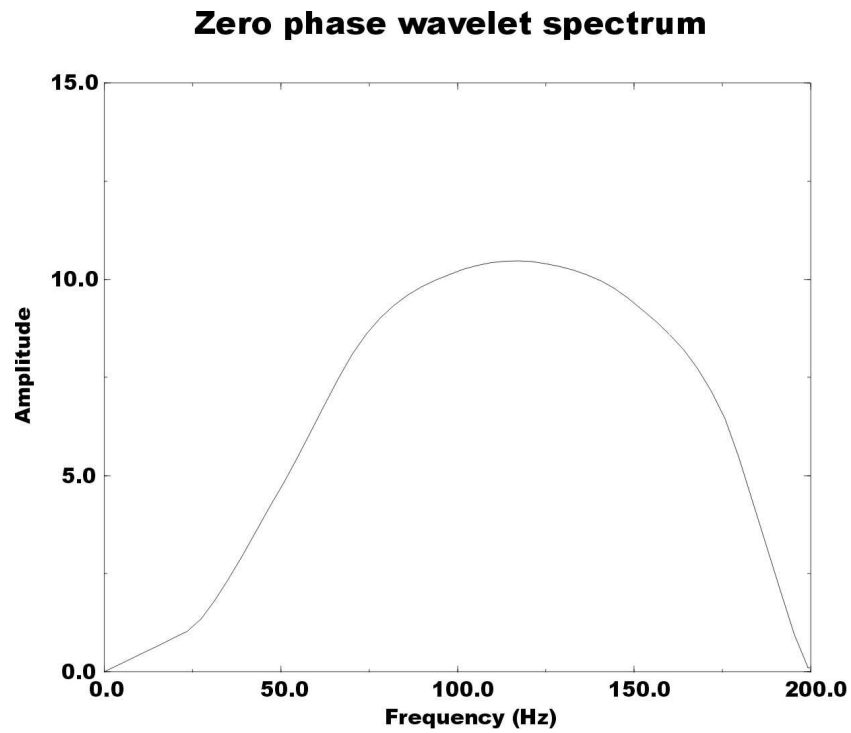


**Figure 3.10:** *The zero phase wavelet amplitude spectrum.*

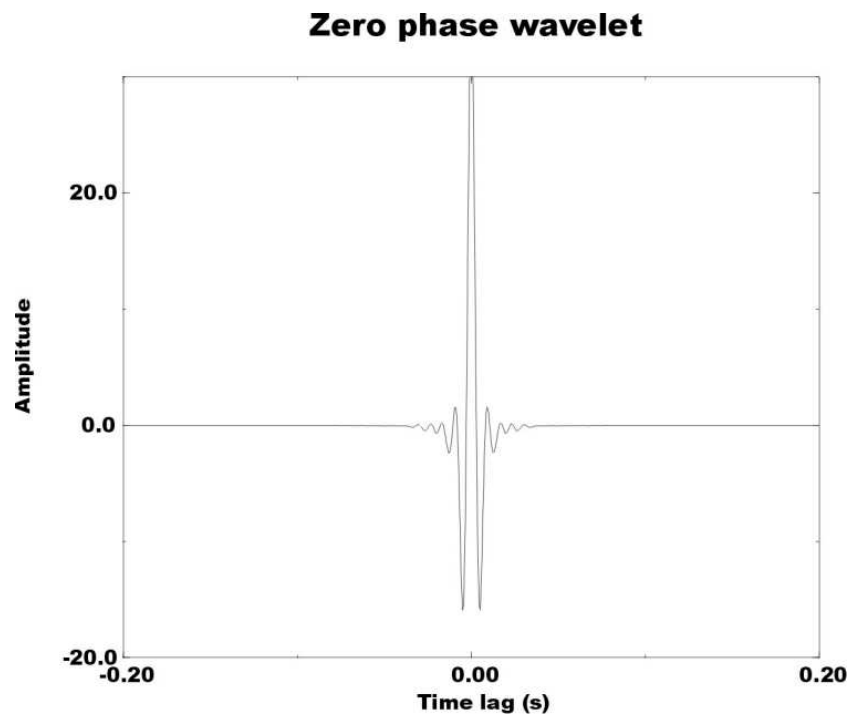


**Figure 3.11:** *The zero phase wavelet that each measured source signature was deconvolved to.*

The aim is now to take the single sweep  $s(t)$ , and find a filter  $f(t)$  that converts it to the shorter zero phase wavelet  $d(t)$ , as shown in Figure 3.11. The operation performed is a convolution:

$$s(t) * f(t) = d(t) \quad (3.1)$$

$f(t)$  can be found by using the Wiener normal equations (as described in detail in Chapter 5, Section 5.3.3), with  $s(t)$  as the known input and  $d(t)$  as the desired output. However,  $s(t)$  is 12 seconds long with a 0.5 ms sampling rate, which represents about 24,000 samples. The number of operations for this process in the time domain is of the order  $n^2$ , where  $n$  is the number of samples. One filter requires around 5 minutes on a Sun workstation. Clearly this is not an efficient strategy for this data set. Ziolkowski et al. [87] solved this problem by transforming the operation to the frequency domain where the convolution becomes a multiplication. Transforming Equation 3.1 to the frequency domain and rearranging yields:

$$F(\omega) = \frac{D(\omega)}{S(\omega)} \quad (3.2)$$

This division is unstable since the amplitude spectrum of the sweep goes to zero at certain frequencies; stabilisation is achieved through addition of a small amount of white noise,  $\epsilon$ .

$$F(\omega) \approx \frac{D(\omega)\bar{S}(\omega)}{|S(\omega)|^2 + \epsilon}, \quad (3.3)$$

Where  $\bar{S}(\omega)$  is the complex conjugate of  $S(\omega)$ , Figure 3.12 is the result of convolving the filter corresponding to the sweep in Figure 3.3 with the signal shown in Figure 3.9. The improvement in resolution is impressive. The major information in the signal is contained in the first second this translates to a 12-fold reduction in data volume. The convolution was performed as a multiplication in the frequency domain. The filter computation and the convolution for all 15 channels takes about 5 minutes on a Sun workstation, this represents a significant improvement in performance.

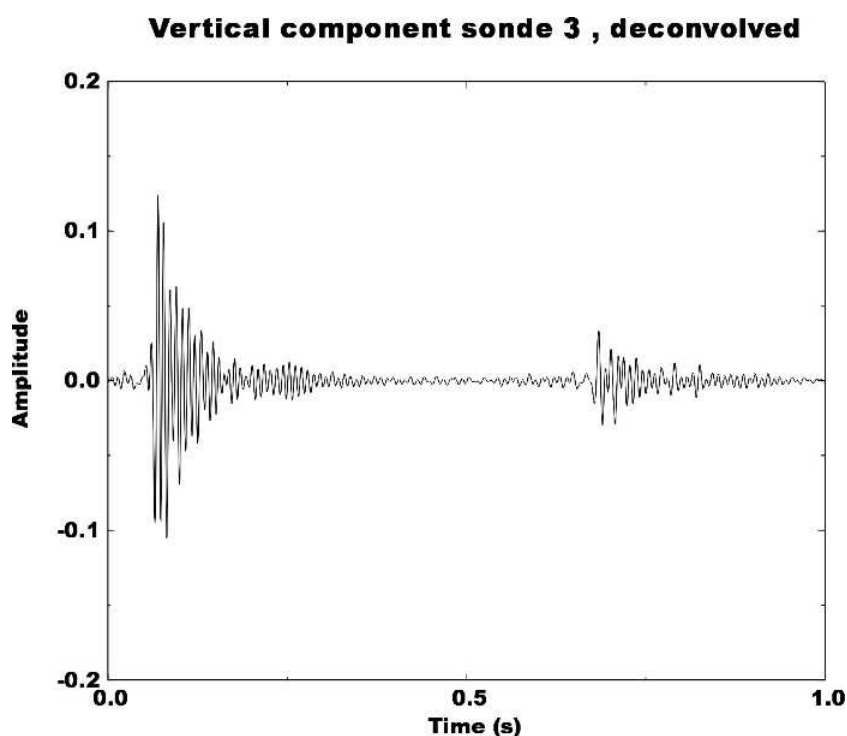


**Figure 3.12:** *The result of the deconvolution, using the zero phase wavelet in Figure 3.11.*

### 3.5 Data analysis and results

All the deconvolution operations were performed on a shot-to-shot basis, with a unique filter being computed for each shot. This ensures that not only is shot-to-shot variability of the source eliminated, but also that no wavelet variability is introduced in the processing. This is essential in order to prevent false interpretations of wavelet behaviour.

One set of the stacked horizontal components of sondes 1-4 for 4 shots at the same depth are shown in Figure 3.13. Whilst each sonde records two horizontal components only one set is shown, to avoid repetition since the arrivals are similar on both. Sonde 5 did not clamp above 1460 ft, and is therefore not used in the analysis. The only arrival that can be seen is the tube-wave which has a move-out of about 4500 ft/s; it can be seen to be consistent in shape for each sonde. On the triaxial geophone package the horizontal components are orientated at right angles to each other and at 45 to the airgun azimuth. Using the triangle law the radial direction is the result of the addition of the components, while the tangential or transverse direction will result from the subtraction of the two components.

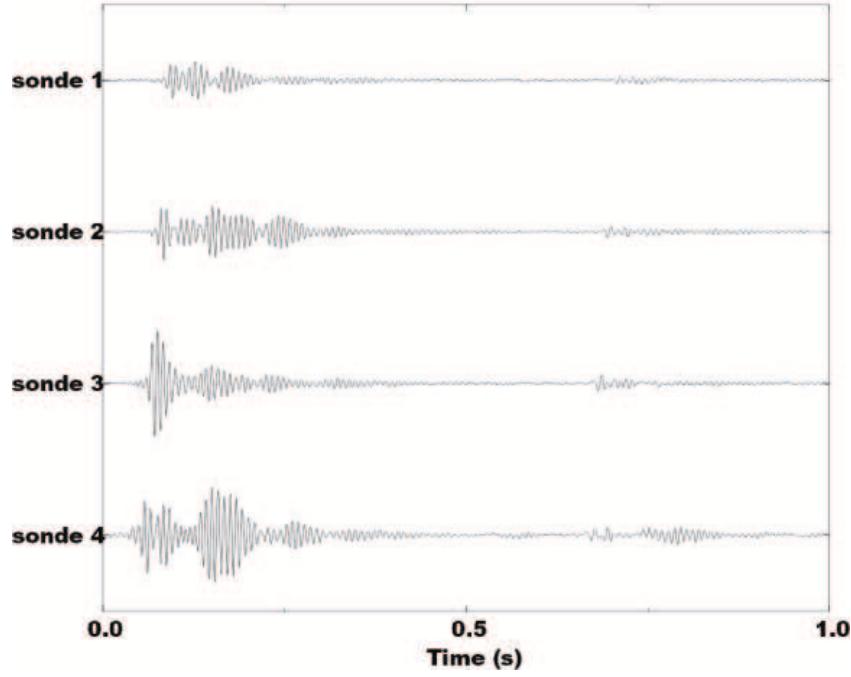


**Figure 3.13:** *Stack of four horizontal component common shot gathers, for consecutive shots at the same depth.*

In theory tube-wave energy is negligible in the tangential direction [68], subtraction of the horizontal components on each sonde should therefore yield a record with the tube-wave removed to show any body wave reflections that are present.

Figure 3.14 is the result of rotating the scaled traces from Figure 3.13. Tube waves are still present and there are no identifiable body-wave arrivals. The conclusion is that it is not possible to remove the tube waves using this strategy. This does not refute the theory that tube waves do not exist in the tangential direction, rather it is more than likely that the results were due to the fact that the tangential direction is difficult to find due to the circular polarization of the source wavefield, which is explained as follows.

The notion of circular polarization can be understood by comparison of the source wavefield to electromagnetic radiation [31], consider the motion of the eccentric mass within the source as a rotating electric field vector. The tip of this vector describes a circle as time progresses. There are two forms of circular polarization, right handed and left handed, corresponding to clockwise and counter clockwise rotation of the field vector. The vector at a point in time draws out a helix along the direction of propagation.

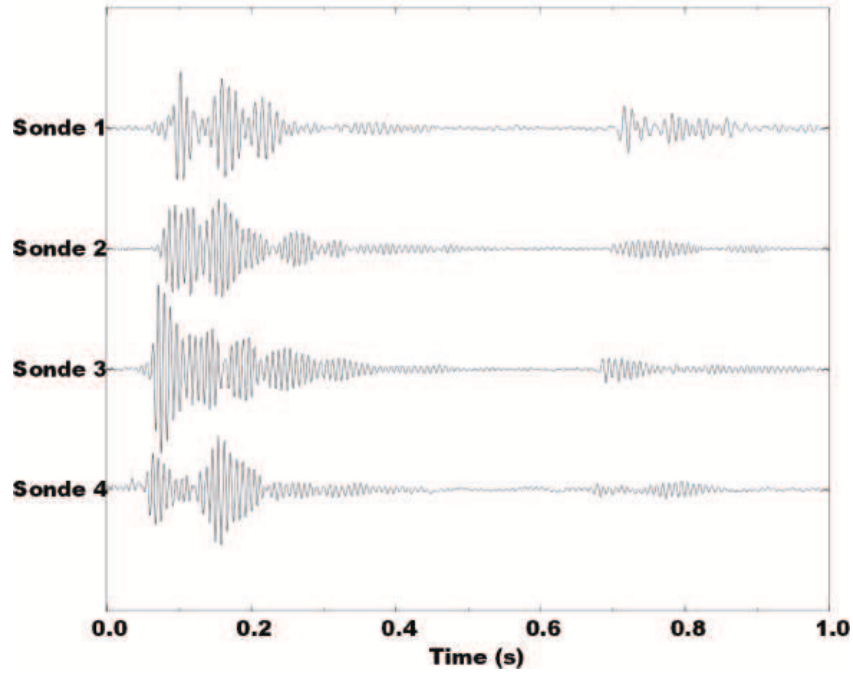


**Figure 3.14:** *The result of subtracting the horizontal recordings of Figure 3.13 to yield the transverse direction.*

Daley and Cox [18] describe a method to decompose the circularly polarised wavefield of the OVS source into linear equivalents. What follows is a brief overview of the method: cw and ccw rotations of the eccentric mass can be described in rectangular coordinates. The  $x$  axis is aligned with the source monitor geophone, and the  $y$  axis is normal to this, in the horizontal plane, and the angle  $\theta$  is measured from the  $x$ -axis to the centre of mass as in Figure 3.15. Consider a generalised source function  $s(f)$ , where  $f = \omega/2\pi$ , the frequency of the rotating eccentric mass  $\theta = \omega t$ . Assuming radial displacement  $U$  at the centre of mass location, the linear components of displacement  $x$  and  $y$  ( $u_x$  and  $u_y$ ) can be related to  $\theta$  for cw and ccw motion.

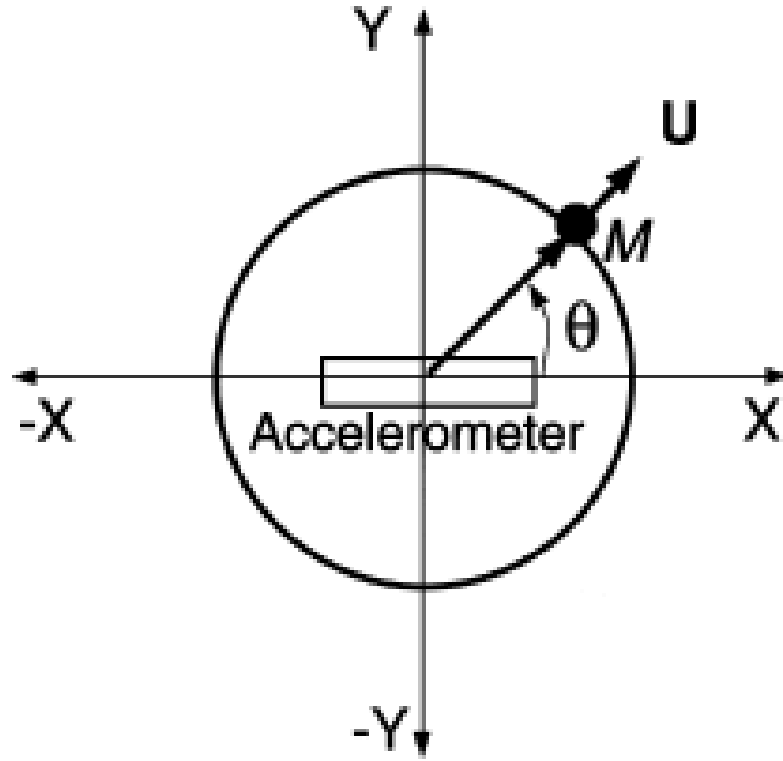


**Figure 3.15:** Schematic model of orbital vibrator. The eccentric mass is represented by its center of mass  $M$  rotated in the horizontal plane. The angle  $\theta$  is measured from the  $x$ -axis to  $M$ . The center of mass has a radial displacement  $U$ . Taken from Daley [18].

Let  $u_{cwx}$  and  $u_{cwy}$  be the  $x$ - and  $y$ -components of  $U_{cw}$  (clockwise displacement), and let  $u_{ccwx}$  and  $u_{ccwy}$  be the equivalents for counterclockwise displacement  $U_{ccw}$ . Assuming displacement  $U$  has equal amplitude  $A$  for all  $\theta$  the following can be written:

$$u_{cwx} = A \cos(\theta), \quad (3.4)$$

$$u_{cwy} = A \sin(\theta), \quad (3.5)$$

$$u_{ccwx} = A \cos(-\theta) = A \cos(\theta), \quad (3.6)$$

$$u_{ccwy} = A \sin(-\theta) = -A \sin(\theta). \quad (3.7)$$

The next step is to combine the recorded cw and ccw wavefields to obtain the linear equivalents of the source motion  $u_x(\omega t)$  and  $u_y(\omega t)$

$u_x(\omega t)$  is obtained by addition of the clockwise and counterclockwise recordings:

$$u_x(\omega t) = U_{cw} + U_{ccw} = u_{cwx} + u_{cwy} + u_{ccwx} + u_{ccwy} \quad (3.8)$$

$$A \cos(\omega t) + A \sin(\omega t) + A \cos(\omega t) - A \sin(\omega t) = 2A \cos(\omega t). \quad (3.9)$$

The  $y$  component  $u_y(\omega t)$  is obtained in a similar fashion by subtracting the cw and ccw recordings to yield

$$u_y(\omega t) = 2A \sin(\omega t) \quad (3.10)$$

The 90 degree phase difference is removed by the application of a Hilbert transform. The result of this process is to decompose the data into two independent sources oscillating sinusoidally along the  $x$  and  $y$ -axes.

However, in the Uniwell experiment the source was only rotated in one direction and this makes it impossible to decompose the wavefield into these linearly polarised equivalents.

Figure 3.16 is a common-offset gather for the vertical component of sonde 3. Two things can be seen. Firstly, the tube-wave arrival is essentially the same on each trace; secondly and more importantly, there is a coherent arrival on each trace with a move-out equal to half the tube-wave speed. The dip of the event shows that it is the result of a reflection below the source. Looking at the a deeper recording made with the source at 1130 ft below the source level in Figure 3.16 the event is still visible but it arrives much earlier. The event can be identified as a tube-wave reflected from the base of the hole. Figure 3.17 illustrates that as the source is moved up by 10ft the path length of the reflection increases by 20 ft; therefore on a common offset gather its apparent velocity is exactly half its true velocity.

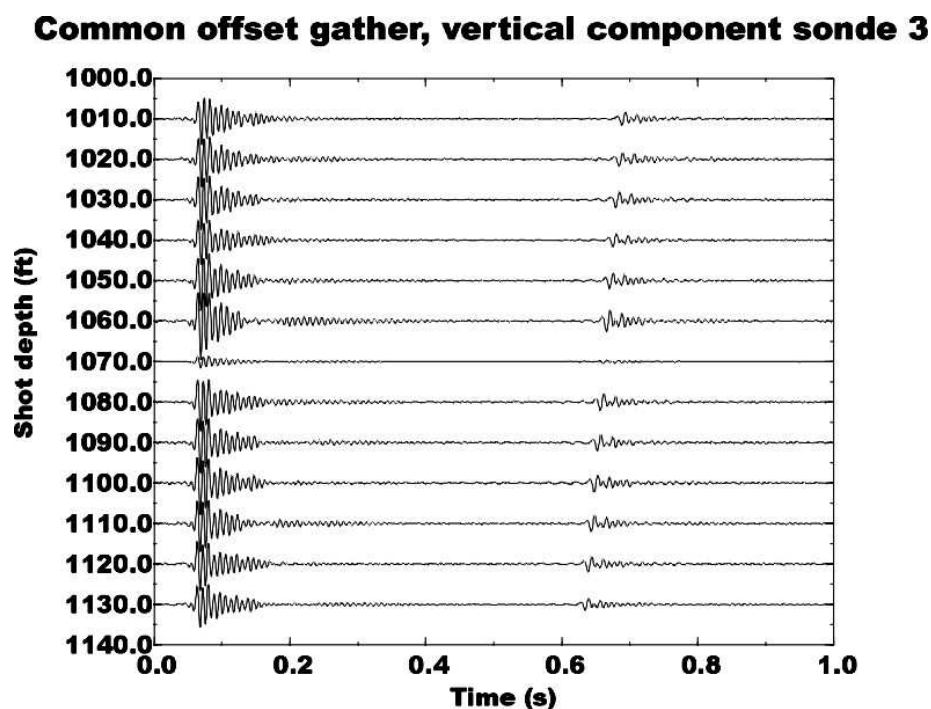


**Figure 3.16:** Common offset gather, axial component, after deconvolution for 13 shot positions.

At a header depth of 1000ft the reflected tube-wave arrival comes in long after any body waves. Therefore it can be assumed to be a good representation of the tube-wave, uncontaminated by body waves. A better estimate can be obtained by stacking all the traces in the common offset gather. In order to do this the move-out of the reflected tube-wave, must be corrected for by applying a time delay to all the traces below the final record. The linear moveout velocity will be the velocity that corresponds to the most coherent stack as shown in Figure 3.18, with the result of the stack being the best estimate of the tube-wave shape for that particular shot.

Each trace is windowed so that the tube-wave event begins at zero time and each component is added together. The result is scaled by  $1/N$  where  $N$  corresponds to the number of traces. Because of physical variation between the sondes a new tube-wave must be calculated for each one.

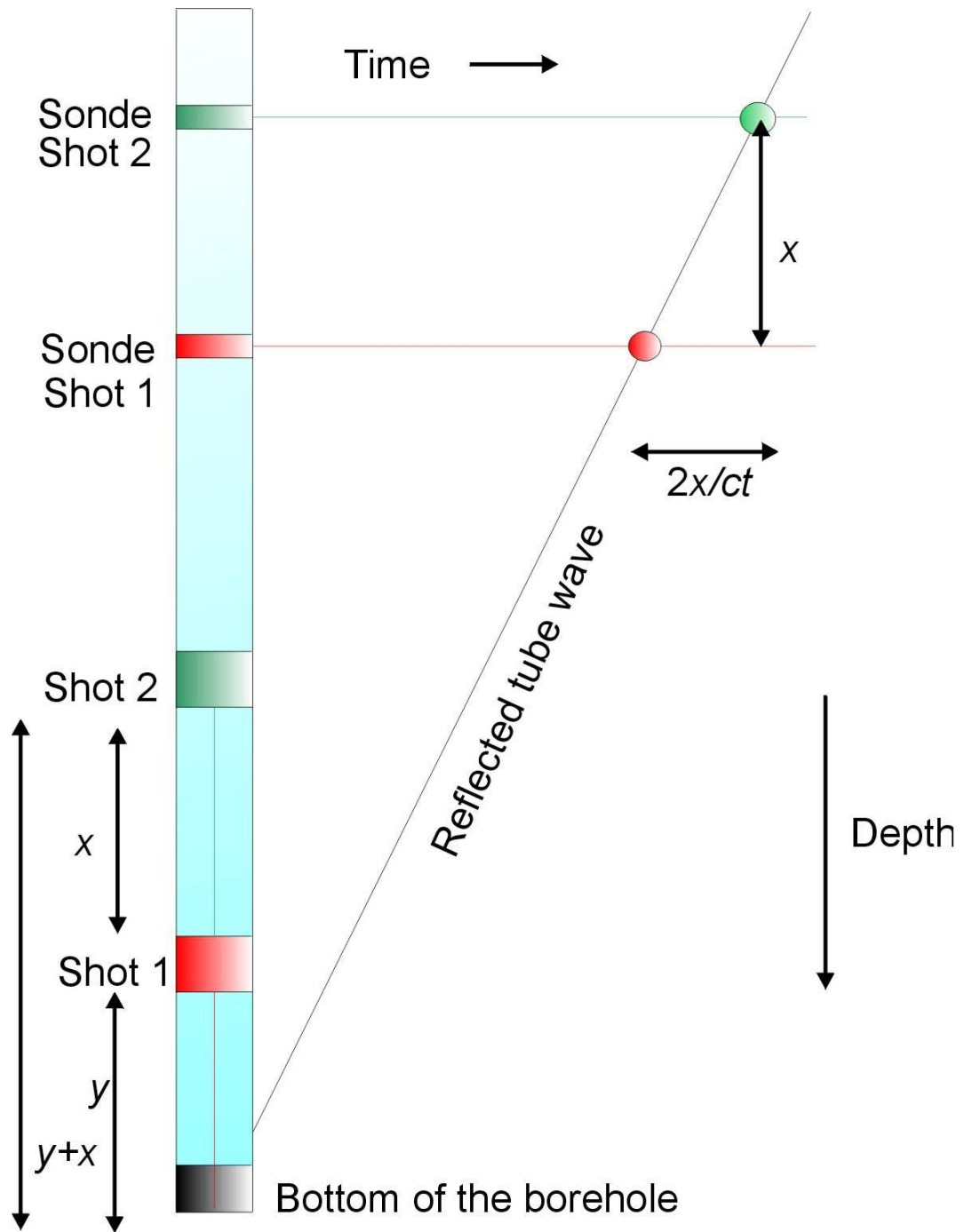


**Figure 3.17:** Diagram showing how the tube-wave is reflected from the base of the hole.

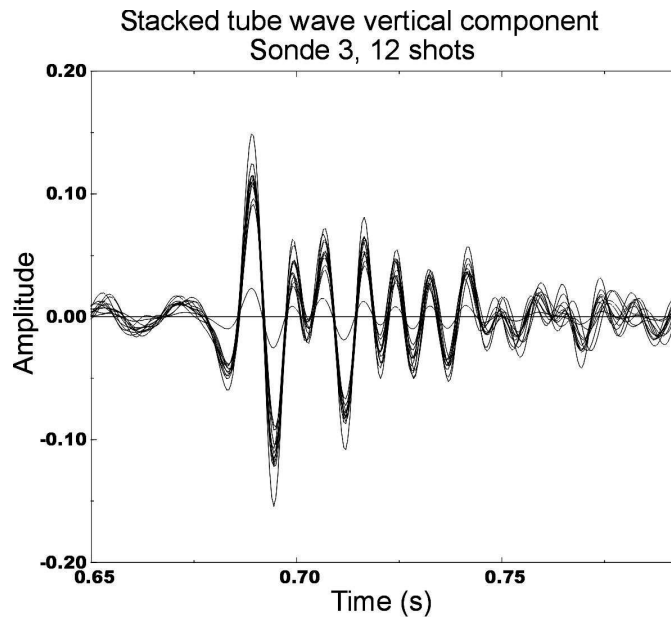


**Figure 3.18:** *Result of shifting recordings made at different depth intervals forward to eliminate the tube-wave move-out.*

Tube waves could be eliminated by utilising the wave property of destructive interference, by adding the stacked tube-wave from the recorded data with the opposite polarity, or directly by subtracting the stacked tube-wave from the data. The major issue here is scaling and timing. It is essential to know when the direct tube-wave arrives, if the timing is wrong. Then the interference will be unknown, possibly resulting in more tube-wave energy being added to the signal. Similarly, if the scaling is wrong either not enough tube-wave will be removed, or again more will be added in. Cross-correlation of the stacked tube-wave and the signal produces an inconclusive arrival time as shown in Figure 3.19, due to the ringing of the signal and the fact that the underlying body wave energy changes the character of the tube-wave arrival. Figure 3.20 shows the result of subtracting the stacked tube-wave, using the delay interpreted from the cross-correlation. Again this fails to substantially remove tube-wave energy from the signal. Clearly resolution is still a problem, despite the success of the initial deconvolution.

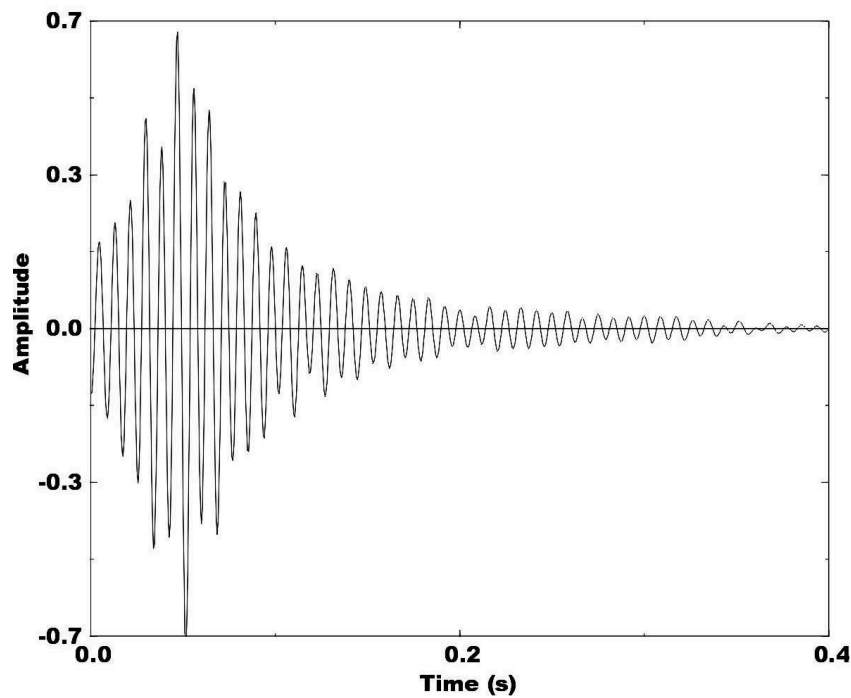


**Figure 3.19:** *The result of the cross-correlation of the stacked tube-wave with the first 400 ms of the trace recorded on the vertical component sonde 3.*

The next step is to try and improve the resolution of the data further. Hardage [32] states that the tube-wave has the same shape as the source wavelet that creates it, and subsequently any reflected tube waves also have the same wavelet shape as the source. This wavelet should have the same shape throughout the whole data set, since it was deconvolved to the same zero phase wavelet. It is important to note that the tube-wave shape is the same for every shot after deconvolution only on the same receiver on a common offset gather as in Figure 3.16. It is clearly not the same shape on different sondes 3.13. This could be due to the fact that the sondes are separated by 15m, so different noise conditions could be reasonably expected in the vicinity of each sonde, and to this there may be additional arrivals on different sondes which distort the tube-wave.

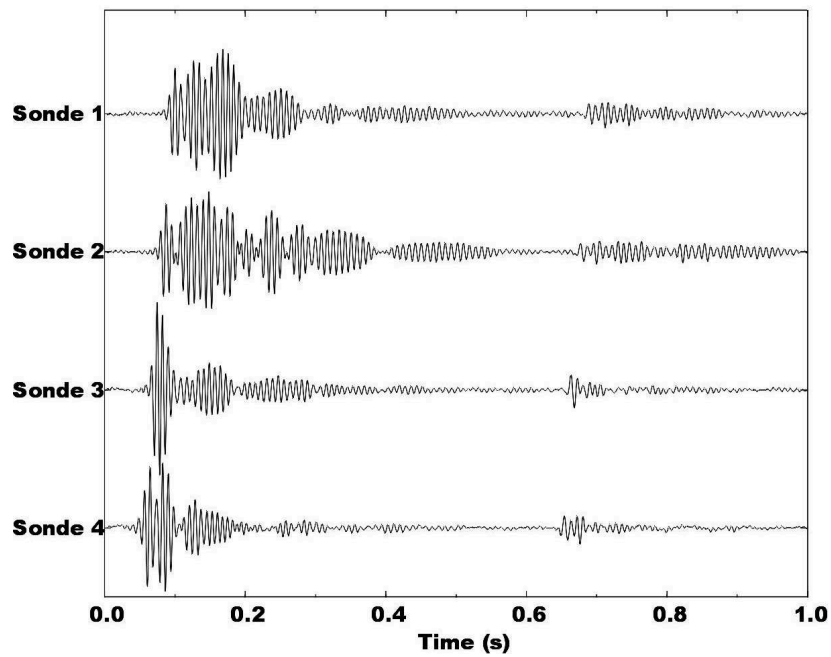


**Figure 3.20:** Common shot gather, vertical component, after stacked tube-wave has been subtracted, using a delay interpolated from Figure 3.19.

However, the fact that the tube-wave is constant on the common offset means that a stacked tube-wave can be calculated for each sonde and used as an input to perform a second deconvolution, with a zero phase wavelet as the desired output. The second deconvolution should compress the tube-wave, and perhaps the body waves, so that the tube-wave arrival will be more obvious. It is also possible that with increased resolution the body wave arrival will appear as a separate event before the tube-wave arrival, with a move-out equal to the P-wave velocity in the medium. Since the body wave is a refracted arrival and the tube-wave is a direct arrival as shown in Figure 3.21, plotting their move-out on an appropriate scale, should result in the tube-wave intersecting the origin. The P-wave should then intersect the x-axis, with a positive offset, as shown in Figure 3.22. The origin of the  $x$  and  $y$  axes represent the space time co-ordinates of the source before it fires. It is essential that the stacked tube-wave has enough bandwidth to be compressed further, or the deconvolution will have no significant effect.

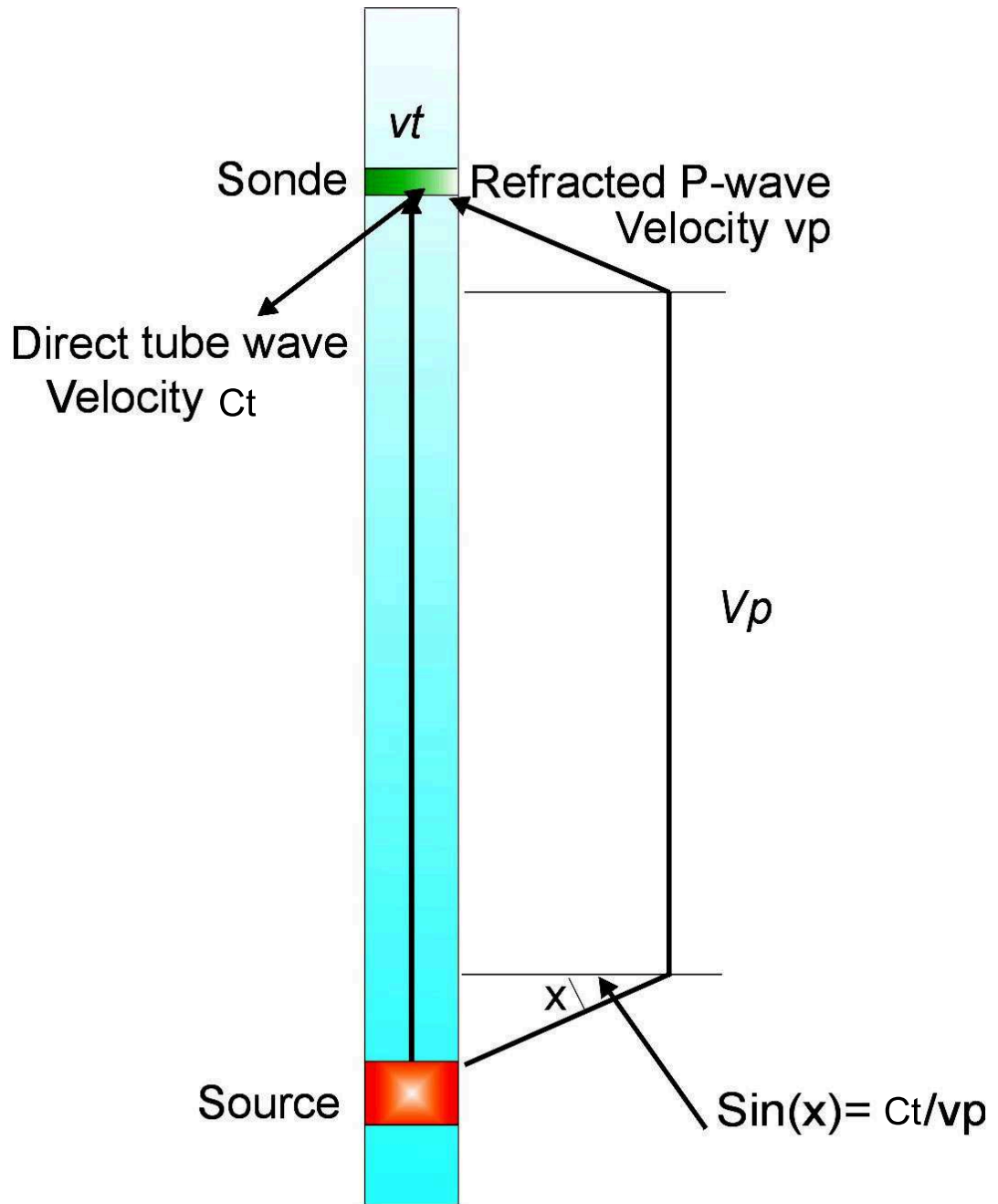


**Figure 3.21:** Diagram showing the P-wave refracted with an angle  $x$  which is dependent on  $C_t$  the tube-wave velocity, the P-wave velocity in the fluid, and  $V_p$  the P-wave velocity in the surrounding medium.

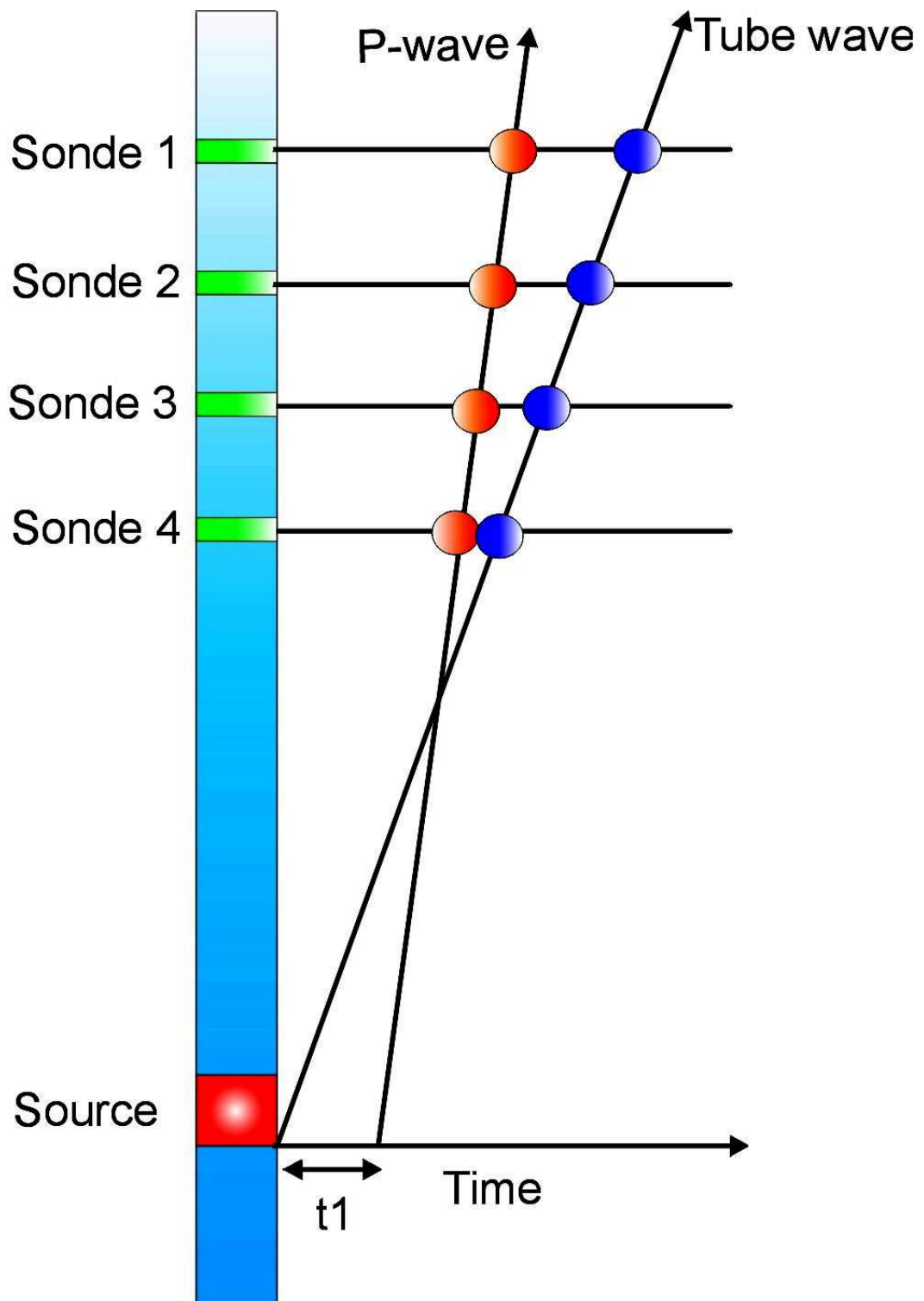


**Figure 3.22:** Diagram showing that the refracted P-wave will be offset from the direct tube-wave by a delay equal to  $t_1$ .

### 3.6 Tube wave deconvolution Results

The Reflected tube-wave stacks with maximum coherency at a velocity of 4407 ft/s on vertical component, as shown in Figure 3.18, this was believed to represent a good estimate of the true tube-wave shape. The reflected tube-wave in the vertical direction has a broadband frequency spectrum, which is similar to that in the horizontal direction as shown in Figure 3.23. This illustrates the problem with F-K filtering, as the bandwidth of the tube-wave is similar to that of the body waves. Because of this F-K filtering would remove most of the body wave energy as well.

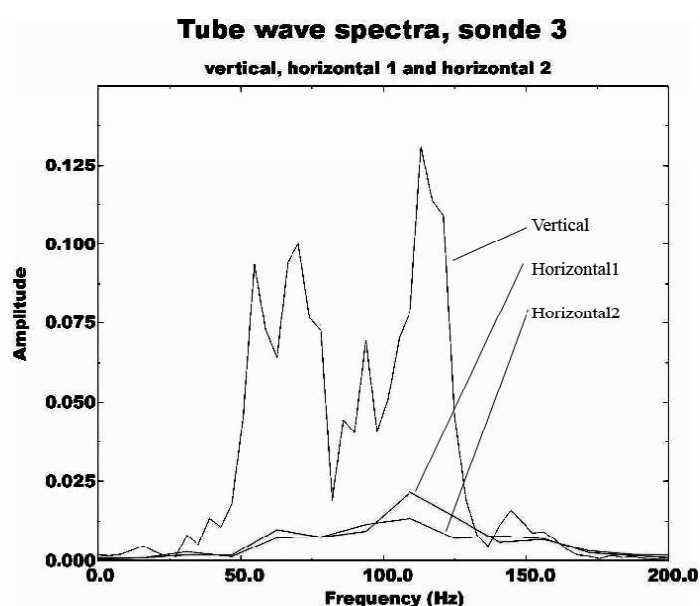


**Figure 3.23:** Tube wave spectrum in the horizontal and vertical directions.

Figure 3.24 shows the common shot gather for the vertical components of sondes 1-4 before tube-wave deconvolution. This secondary processing step was applied in the same manner as the initial deconvolution, by replacing the source signature with the stacked tube wave. The result of the tube-wave deconvolution is shown in Figure 3.25.

Comparison of Figure 3.25 with Figure 3.24 shows that some new arrivals are now present before the main tube-wave arrivals. These could be interpreted as refracted body wave arrivals. In order to ascertain whether they are indeed refractions and to find the location of the refractor, it is necessary to plot the results on a scale which has the source location at the origin of the axis. Figure 3.26 illustrates this. The new arrivals can be seen to have a positive offset on the

$x$ -axis, this is approximately equal to .2 ms. This represents the transit time of the direct wave to the refractor. Assuming a P-wave speed of 2020 ms this puts the refractor at distance of 0.400 m. This is consistent with a refracted P-wave from the source. Also the move-out velocities of the first and second arrivals are  $2012ms^{-1}$  and  $1280ms^{-1}$ , respectively. This is consistent with a P-wave and a tube wave.

Unfortunately, the result in Figure 3.26 is not conclusive. The arrivals are not the same shape on every sonde. Looking at sonde 1 and sonde 2 it can be seen that the tube-wave is not as well compressed here, and the arrival is not as definite as on sonde 3 and 4. This is possibly due to the tube-wave shape being slightly different. Which is likely to be due to poor clamping of the receivers, this was known to have been an issue.

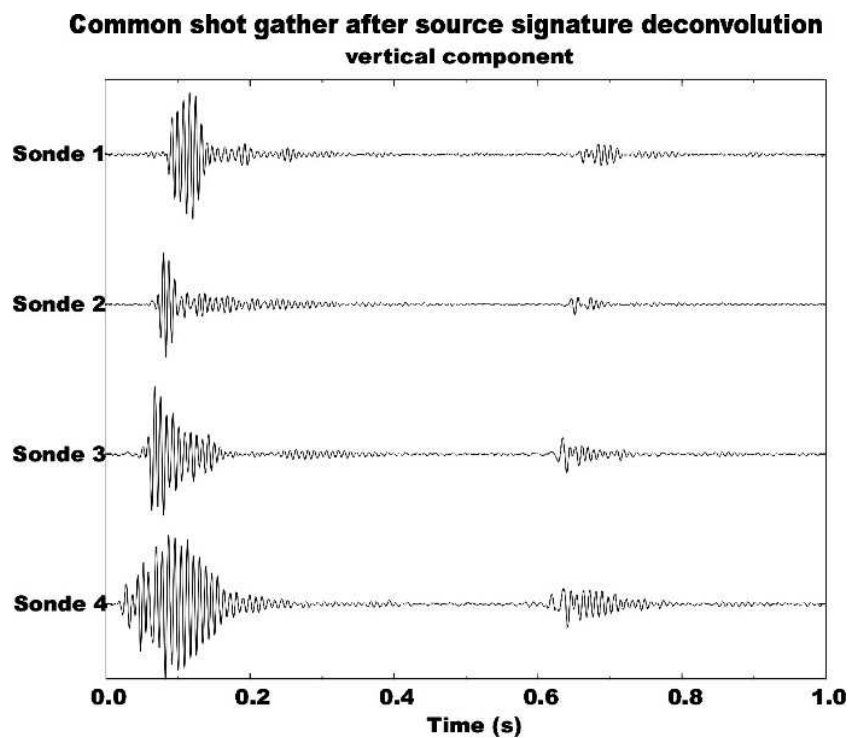


**Figure 3.24:** Vertical components of a common shot gather before the second deconvolution, showing only tube-wave first arrivals.

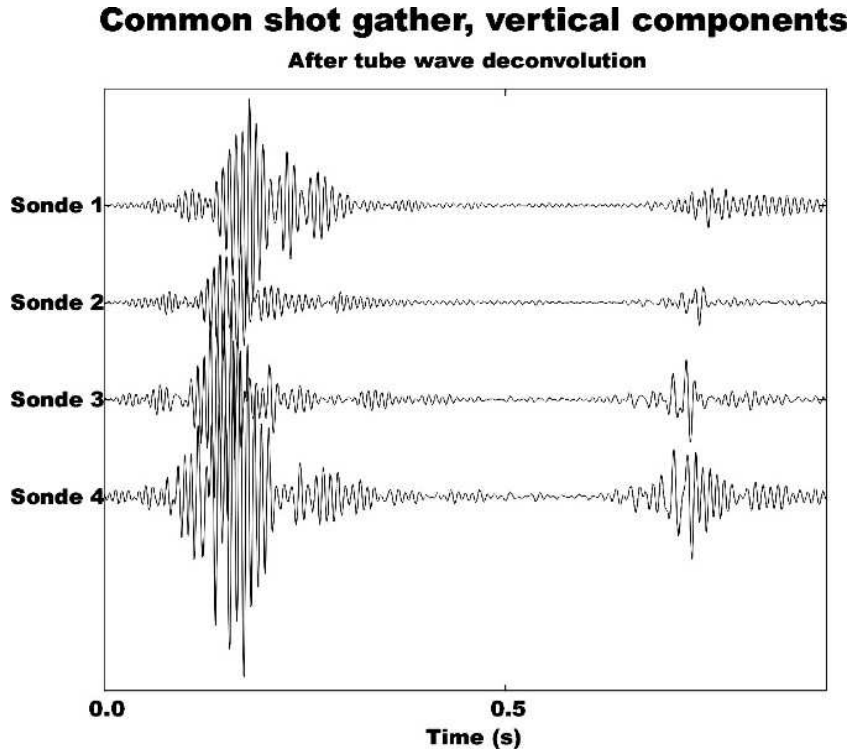


**Figure 3.25:** *Result of the tube-wave deconvolution.*

### 3.6.1 Empirical mode decomposition

The EMD technique [33] was applied to a number of deconvolved common shot gathers from the Uniwell experiment. However, only two meaningful IMFs were obtained the rest of the IMFs lay outside of the frequency range of interest. The information that could be obtained from results was rather limited because of this. However, there is an event which has a move-out speed equal to the expected P-wave speed. Unfortunately the low number of receivers in the gather along with the limitations of the decomposition make this result ambiguous.

Figure 3.27 shows a deconvolved vertical common shot gather, for sondes 1-4, the tube-wave arrival is clearly visible, no other arrivals can be interpreted. Application of the EMD technique to this gather yields eleven IMFs of which only two lie within the 0-200 Hz frequency range, and only the first contains any significant data.

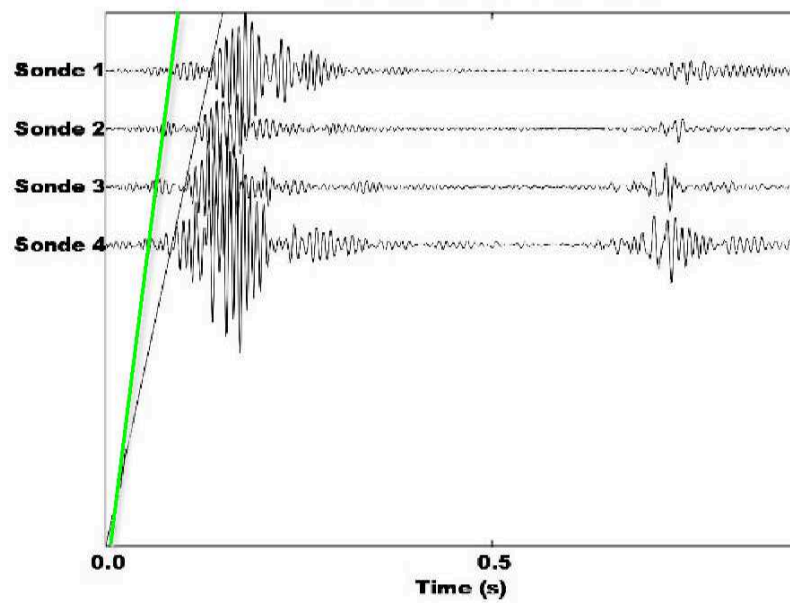


**Figure 3.26:** Result of the second deconvolution plotted on a scale where the source is at the origin.

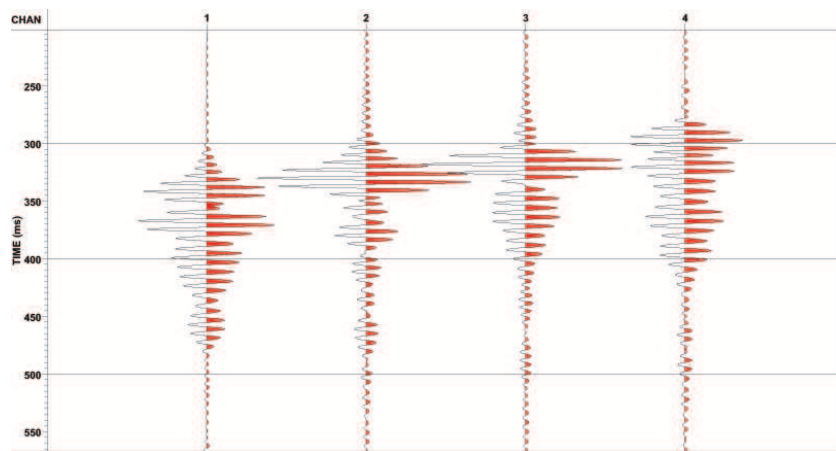


**Figure 3.27:** Vertical component Common shot gather for Sondes 1-4 after source signature deconvolution.

Figure 3.28 shows a common shot gather of the first IMFs of Figure 3.27. The high amplitude arrival is still present, but there is also a small arrival which is overlain by the tube-wave on sonde 4, but moves out with a greater speed. The move-out of the tube-wave has been calculated to be  $1450\text{ms}^{-1}$ , this small event has a move-out of  $2000\text{ms}^{-1}$ , Ziolkowski et al. [87] estimated the P-wave velocity to be in the area of  $2010\text{ms}^{-1}$ , they arrived at this

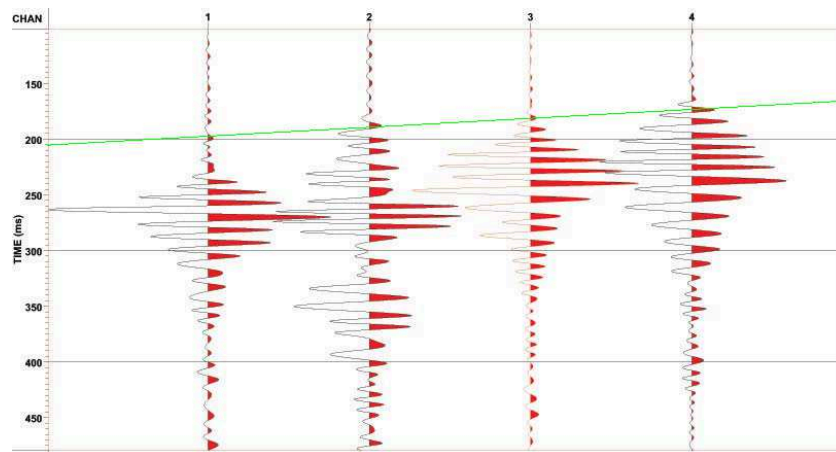


**Figure 3.28:** Vertical Common shot gather for sondes 1-4 after EMD. The green line shows the possible P-wave arrival.

figure using the following method. The P-wave arrival corresponding to the airgun source was identified on the Uniwell geophones and the cemented geophones, this provided an estimate of the velocity between from COG30 (where the airgun source was located) to COG54 and from COG30 to GEO1. Since the distance between the source and all receivers are known the P-wave arrival times can be used to estimate the velocity, this was calculated to be 1820 m/s. Another estimate can be calculated by using the P-wave arrivals on the cemented geophones corresponding to the OVS, this was equal to  $2190\text{ms}^{-1}$ . The P-wave velocity of  $2010\text{ms}^{-1}$  was chosen to lie between these two estimates

The arrival is better defined on sondes 1 and 2, than on sondes 3 and 4, interestingly sondes 1-2 produced more intrinsic mode functions than 3 and 4, leading to the suggestion that the results from 3 and 4 are not as accurate. Figure 3.29 shows the result of applying EMD to another common shot gather from a different part of the data-set. The data here is again from the vertical components, although in this case sonde 5 was clamped, and is therefore included. It can be seen that the arrivals are consistent, most importantly the P-wave arrival comes in at the same place relative to the tube wave, on Sonde 4 and has the same move-out.

It is likely that better results could be obtained by modifying the EMD algorithm to focus on the bandwidth of interest by inserting a band pass filtering step. The results presented here suggest that this is worth investigation.

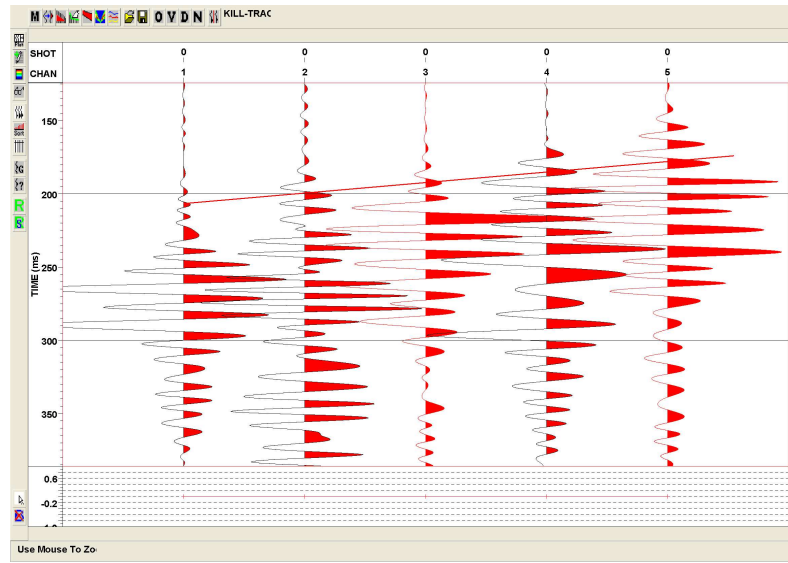


**Figure 3.29:** Common shot gather from different part of the data set showing consistent arrival events, after processing with EMD.

### 3.7 Conclusions

The methods described in this chapter have achieved some success in attenuating the tube-wave noise. However, they are not completely successful and some of the results are ambiguous. Various conclusions can be drawn from this. Perhaps the most obvious is that a fluid-coupled source like the orbital vibrator is not ideal for single well imaging due to large tube-wave generation. Another disadvantage of the orbital vibrator source is the need for it to be spun in two opposite directions in order to separate the circularly polarized waves into linear equivalents.

In the Uniwell experiment the source was spun in one direction. Therefore it was impossible to decompose the wave field. It is questionable, therefore, whether the rotation of the horizontal components could be expected to produce the tangential component. The empirical mode decomposition and tube-wave deconvolution techniques are promising. EMD is perhaps the most interesting technique, promising the chance to separate out different wave modes. Unfortunately at present it is a broadband technique operating over the whole frequency range. The decomposition needs to be restricted to the bandwidth of interest, 0-200 Hz in this case. At the moment this is not possible. However, there is ongoing research in this field [41]. Once this drawback is removed EMD, could become a useful technique for removing noise from seismic data.

The main conclusion to be taken from this work on the Uniwell data are that the data processing strategy is sound and EMD is a promising if currently limited technique. However, the major drawback remains the downhole source. The unsuitability of a fluid-coupled source, led to the next step in the project, the design of a clamped source, which would in theory generate less tube-wave energy. The next chapter describes the research, development and testing of this source, which was based around a magnetostrictive actuator and a sophisticated driving method.

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# Chapter 4

## Design development and construction of a new downhole source

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### 4.1 Introduction

This chapter details the work done to develop, test, and construct the new magnetostrictive downhole source discussed in Chapter 1. It consists of two main sections. The first deals with the initial prototyping work where a small fluid-filled borehole model was designed and tested in order to assess various different driving and processing strategies, with the view to implement the most satisfactory in the final source. A description is given of the borehole model and the data acquisition and processing strategies and some results are presented from the testing of the source in a wave tank. The second section details how the magnetostrictive source was built and the considerations which dictated the design and driving method. This section describes an experiment where the source was inserted and driven within a cored granite block. Data recorded by accelerometers placed on the outside of the block were processed using the method developed for the initial prototype, and the results are discussed. Finally a new design for the mechanical setup of the tool is discussed, the need for which is apparent from the results. The chapter concludes with a discussion of the relative achievements of the design and building work.

### 4.2 Background and initial design considerations

The concept of a downhole seismic source is not new. Airguns, dynamite and piezo-electric sources have all been used downhole for decades. Their deployment is generally in a reverse VSP setup, where the receivers are on the surface and the source downhole, as illustrated in Figure 4.1, or in a cross-well configuration where the receivers are located in another borehole some distance away from the source.

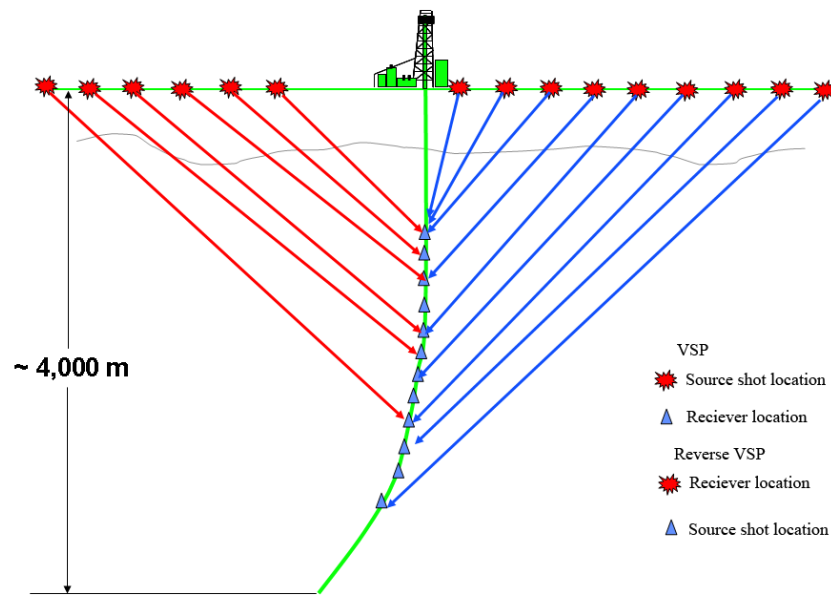


**Figure 4.1:** Normal VSP setup with source on the surface and receivers downhole, in a reverse VSP the source positions are replaced by receivers and vice versa.

However, it is notable that very few if any downhole sources have ever been designed with single well imaging in mind; that is to say, none of the previous sources were designed with the intention of placing receivers in the same borehole, which may explain why most downhole sources are fluid-coupled. Being fluid-coupled means there is no chance of the source sticking in the hole, no chance of the clamping failing which would lead to lengthy and more importantly costly delays. Also in a crosswell or reverse VSP setup tube waves are more of a nuisance than a problem, as they invariably arrive after the body waves. In a single well imaging setup all this changes, as is evident from the results of the Uniwell experiment. The shortcomings of fluid-coupled sources are very evident in a single well imaging setup. It is clear therefore that a different design is required for a single well imaging downhole source, with the most important design consideration being that the source transfer much less energy to the fluid. The obvious choice therefore is a clamped source. Fortunately for the work detailed here some research had already gone into developing such a source.

From 1992-1997 Sandia National Laboratory were engaged in developing a magnetostrictive borehole source. This was designed to be deployed in shallow boreholes for environmental applications such as ground water monitoring etc. The novelty of the source was in part the use of a magnetostrictive actuator, consisting of a rod made from Terfanol-D, a material which

changes length in response to a magnetic field. This was attached via a push-rod to a large reaction mass. The actuator was driven with a chirp signal and the reaction mass was designed to be large enough to push against, as in a mechanical vibrator. The mechanical clamping of the source transferred this shear energy to the formation. Unfortunately there was a major flaw in the design: the large reaction mass had the unwanted effect of amplifying any resonant modes that were encountered.

The result of driving against the reaction mass was a large back EMF which could burn out the actuator coils and induce large shear stresses in the Terfanol-D rod. As a result it was very difficult to drive the source at a usable level without damaging the actuator coils or shattering the Terfanol-D rod. These fundamental problems led to the project being abandoned and also led to magnetostrictive sources being regarded as fragile and unusable. The following sections describe the design of a new source which built on the lightweight mechanical simplicity of the Sandia source and also addressed the resonance and power problems which made that source unsuitable for single well imaging.

The source design proceeded in two stages which had significant overlap. The first stage, the fundamental redesign of the Sandia source from a reaction mass to the current setup, was initiated before the research detailed in this thesis had begun, and as such only a brief informative description is given. It should be noted that whilst the fluid-filled borehole work is presented first, it was undertaken in tandem with and with a knowledge of the characteristics of the source described in Section 4.4.

### **4.3 The fluid-filled borehole model**

In order to investigate the driving method and data processing strategies a model of a fluid-filled borehole was built as shown in Figure 4.2. This model consisted of a 2 m length of fluid filled PVC tubing with 15 mm outer diameter. The source used to produce the acoustic waves was a piezoelectric plastic device as used extensively in sounders and buzzers. The structure was bonded to an acrylic shoe which clamped tightly to the tube. This provided a means to transmit the vibrations from the device to the fluid. The receivers were of the same type and were mounted in the same way since, by reciprocity, a transducer that acts as a transmitter can also act as a receiver. Initially the receiver was placed 1m away from the transmitter but the spacing was variable.



**Figure 4.2:** *Model of a fluid filled borehole.*

The source was driven by a pulse generator generating a  $20V$   $10\mu s$  duration uni-pole rectangular pulse repeating every  $10ms$  as shown in Figure 4.3. The receiver was a differential amplifier to eject as much mains hum as possible followed by a  $50$  Hz notch filter.

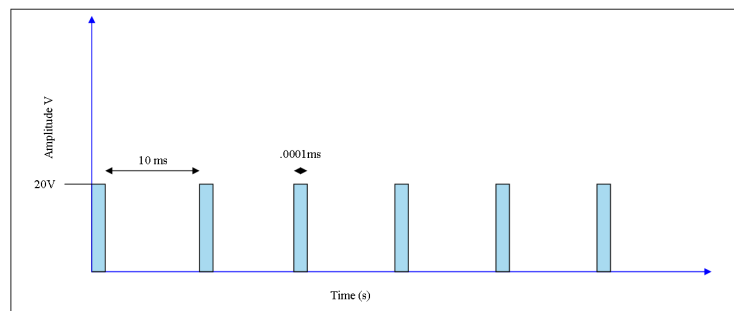


**Figure 4.3:** *The output of the pulse generator.*

The resulting signal, which is the response of the tube to a short pulse cross correlated with transmitted signal, is shown in Figure 4.4. This is similar to the Uniwell data, discussed in the previous section. This represents the tube-wave in the fluid. Later experiments with an array of 3 receivers confirmed that the speed of the event was  $1500$  ms, the speed of sound in water, which confirms that what we are seeing is a wave traveling in the water as opposed to an air wave ( $\approx 316$  ms) or a wave in the PVC ( $\approx 1500$  ms).

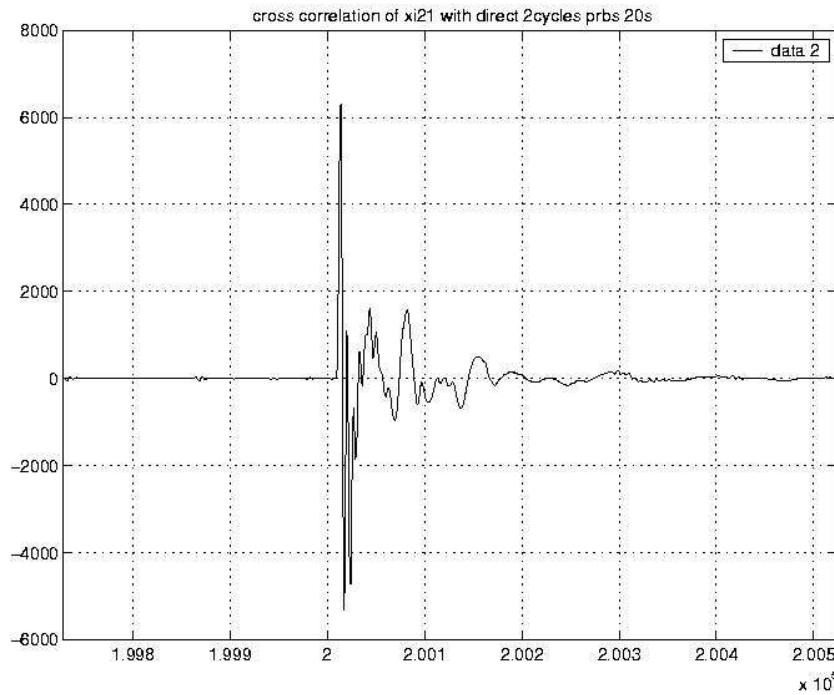


**Figure 4.4:** Result of cross correlation of signal recorded in water filled tube with PRBS.

Once it was clear that the setup would produce a tube-wave in the fluid, a more representative experimental setup was attempted. This consisted of changing the driving signal from a pulse to a coded waveform. This technique is also used in communications where it is called Direct Sequence Spread Spectrum (DSSS) [62].

#### 4.4 Spread spectrum techniques: background, theory and use

The first use of spread spectrum technology was described by an actress and a musician, Hedy Lamarr and George Antheil (US PATENT #2.292.287), who formulated a secure radio link to control torpedos, which was granted a U.S. patent No. 2.292.387 in 1941. This technology was utilised in various applications right up to 1980s, since when it has become increasingly popular as a method of sending out information which is difficult to intercept or jam. It was also put to use at the Lincoln Laboratories in 1971 to calibrate the Large Aperture Seismic Array in Montana. However, this was a rare geophysical application; it is a technique much better known in electrical engineering. Typical modern applications of the basic method include GPS, 3G mobile telecommunication, wireless LAN standards and Blue-tooth.

Spread spectrum is an RF communications system in which the baseband signal bandwidth is intentionally spread over a larger bandwidth by injecting a higher-frequency signal. As a direct consequence, energy used in transmitting the signal is spread over a wider bandwidth and appears as noise. The ratio (in dB) between the spread baseband and the original signal is called processing gain. Typical SS processing gains run from 10dB to 60dB.

The higher frequency signal described here is the spreading code or sequence. The injection of this code can be referred to as the spreading operation. On receipt of the spread spectrum signal at the receiver the original signal can be recovered by removing the code, which can be referred to as a despreading operation. This despreading operation is generally some sort of matched filtering step, utilizing cross-correlation. Therefore it is important that the spreading code has good auto-correlation properties.

It is usual in most spread spectrum applications with multiple users to allocate a unique code to each user. In this application only a single good code is required. This is a code which gives a large auto-correlation peak at zero lag with low side-lobe energy. The auto-correlation function is similar in shape to the zero-phase wavelet which was used to deconvolve the Uniwell data. This has exactly the same effect of compressing arrivals to a sharp impulse. The benefit of this compression, aside from raising the signal up out of the noise, is that with sufficient resolution the tube-wave can be compressed, so that any body waves and reflections which are very close to it become visible.

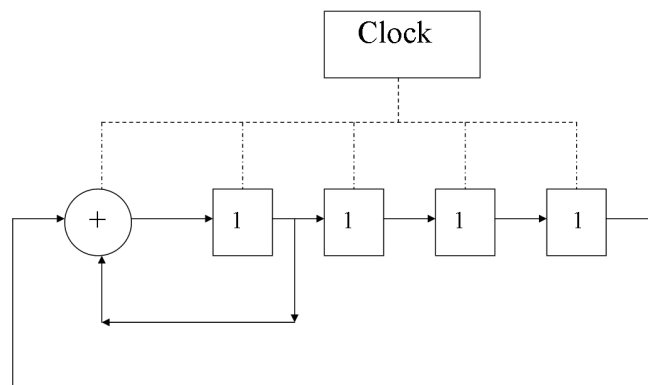


**Figure 4.5:** A simple four-stage shift register capable of generating a 15 digit code.

A Pseudo Random Binary Sequence PRBS was utilised since it has no side lobes in the event that it is run continuously or has at least three repetitions of the sequence with the middle one being used in the correlation calculations. A PRBS sequence is made up of  $N = 2^n - 1$  samples, with a period of  $N \Delta t$  where  $\Delta t$  is the time between samples, its frequency domain representation is comb of delta functions each spaced  $\Delta\omega = 2\pi/N\Delta t$  apart which resemble a Sinc function centred. The most common method used to produce a PRBS is called a feedback shift register. as shown in Figure 4.5. This is made up of an adding device and a clock, which work in the following way. Each stage of the register stores a binary digit. The clock sends out pulses at some specified rate and after each pulse arrives each digit is shifted to the right. The rightmost digit is abandoned and the empty space on the leftmost stage is filled by adding together the rightmost and leftmost digits previously present (before the clock pulse arrived). The digits are modulo 2 summed, i.e  $1 + 1 = 0$  and  $1 + 0 = 1$ . Consider a starting sequence of 1111 after the first clock pulse this becomes 0111 and then 1011, 0101, 1010, 1101.... and so on until the sequence repeats itself, which will be after  $2^4 - 1 = 15$  digits.

The choice of code is not a trivial operation. Good codes must observe a number of rules such as length, auto-correlation, cross-correlation, and orthogonality. Fortunately there are a few popular sequences that have already been calculated which have all the above properties. They include the following: Barker codes, M-sequence and Gold codes. In this case the goal is arrival detection so a large auto-correlation peak with low sides lobes is optimal. The M-sequence or maximal length sequence was used, (hereafter referred to simply as the PRBS sequence), as this gives the best trade-off between main lobe height and side lobe energy. The length of the sequence was 1023 binary digits, therefore after 1023 digits the series repeats itself. The actual PRBS sequence used consisted of a series of these 1M-sequences. We refer to one 1023 digit M-series as a single PRBS. The length of the full PRBS is dependent on the run time and the duration of one binary digit. The auto-correlation properties of the full PRBS sequence can be seen in Figure 4.6.

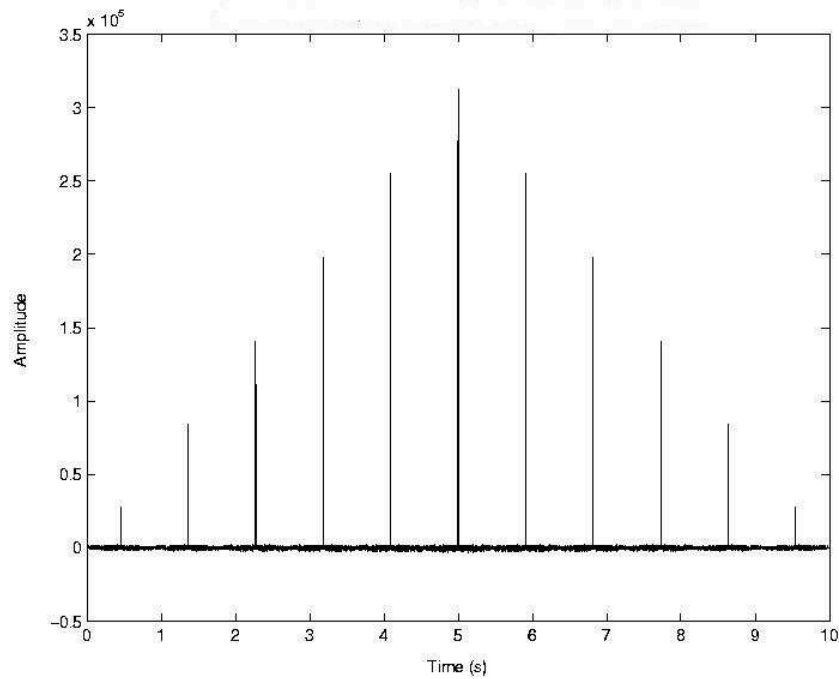


**Figure 4.6:** Auto-correlation of full PRBS signal, with the spike at 5s representing correlation over the full length of the sequence.

#### 4.4.1 Processing and results

An example of the received signal after cross correlation with the PRBS is shown in Figure 4.7. The shape observed here is very similar to the deconvolved Uniwell data with a very clear tube-wave arrival and some additional slower arrivals, which are likely to be reflected tube-waves and waves traveling in the PVC tubing.

After the development of the driving technique the model was transferred to a wave tank as shown in Figures 4.10 and 4.12. Access was kindly provided by Professor Steven Salter of The University of Edinburgh. This allowed the recording of some shots with the model submerged, which provided the closest approximation of a buried fluid-filled borehole that could be achieved at this point. Another benefit of the wave tank was that it represented a very simple homogeneous environment.

The following section describes in detail the data storage and data processing strategy that was developed.

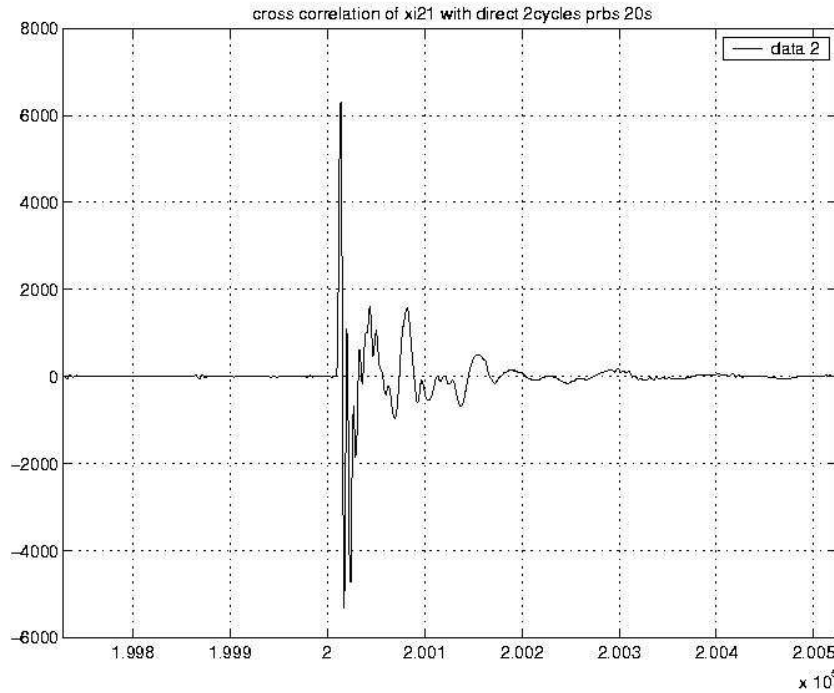


**Figure 4.7:** Result of cross correlation of signal recorded in water filled tube with PRBS.

#### 4.4.2 Data collection and processing in the wave tank

Data collection was performed using Lab-View running on a Pentium II PC. The software collected seven channels of data via a 16 channel, 12 bit analogue to digital converter board (ADC) with programmable gain amplifiers. Sample rate was set at 10 kHz with an anti alias-filter at the Nyquist frequency (5 kHz). The PRBS length used was 1023. The signal processing was done offline using Matlab. This consisted of processing the recorded data into arrays and then cross correlating the signals with the measured initial PRBS signal. which had the result of bringing the signal up out of the noise (despreading operation).

The duration of one binary digit of the PRBS, is 0.9 ms. Therefore after cross correlation the highest temporal resolution in the data can be described by large spike of base width 1.8 ms, or two binary digits. This is confirmed by the auto-correlation in Figure 4.8.

However, the base width of the first arrival (assumed to be a tube-wave) obtained from the cross-correlation of the data received in the tank was 4.5 ms as shown in Figure 4.9. This indicates that there is more than just the direct tube-wave arrival present. It is probable that there are delayed reflections from the ends of the tube.

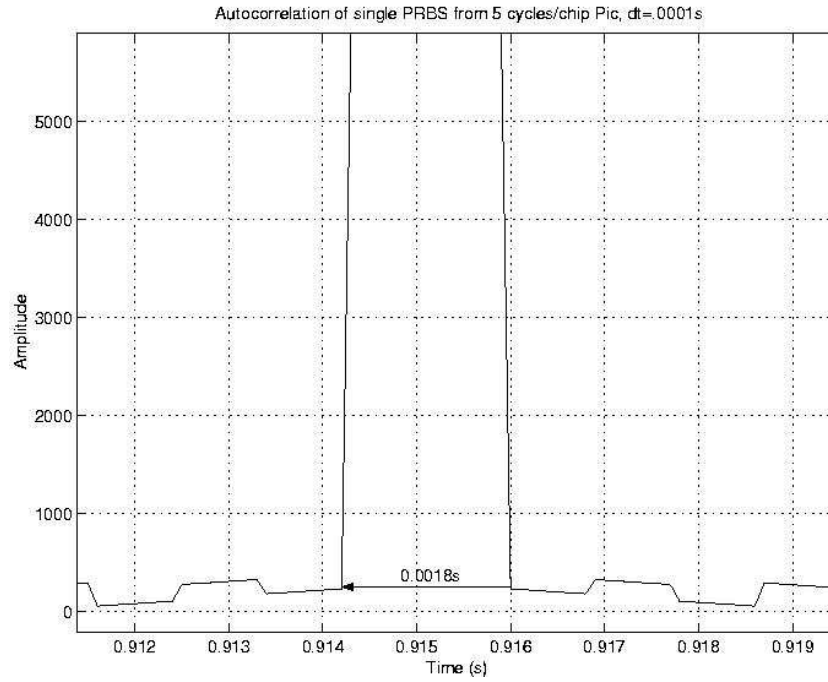


**Figure 4.8:** Showing auto-correlation base width to be 1.8 ms as expected.

This illustrates the resolution problem as discussed earlier, i.e only arrivals which separated by 1.8 ms are fully resolvable. There are at least two such resolvable reflections, as shown in Figure 4.9 : reflection 1 arrives 0.005 ms after the onset of the tube-wave, which is taken as a relative time break due to very small distance between source and receiver; reflection 2 takes twice as long arriving at 0.01 ms. These reflections correspond to a total path length of 3.75 m, and 7.5 m, respectively which fit well with the locations of the sides of the tank, as shown in Figure 4.10.

One of the ways of distinguishing targets from background noise is by the growth rate of their cross correlation function with the PRBS under coherent time averaging. Being signal related, they will grow at rate  $N$  in amplitude when averaged over  $N$  repetitions of the PRBS. However, the noise will only grow at a rate of  $\sqrt{N}$  since its phasor representation exhibits non-coherent addition. This is the basis of the noise cancelation technique known in geophysics as stacking. Each test was run over six repetitions of the PRBS carrier and the whole file cross-correlated. This is equivalent to averaging over six repetitions and resulted in a factor of 6 growth in the main peaks this can be seen by comparison of Figure 4.11 with Figure 4.9 which is the result of averaging over only one PRBS.

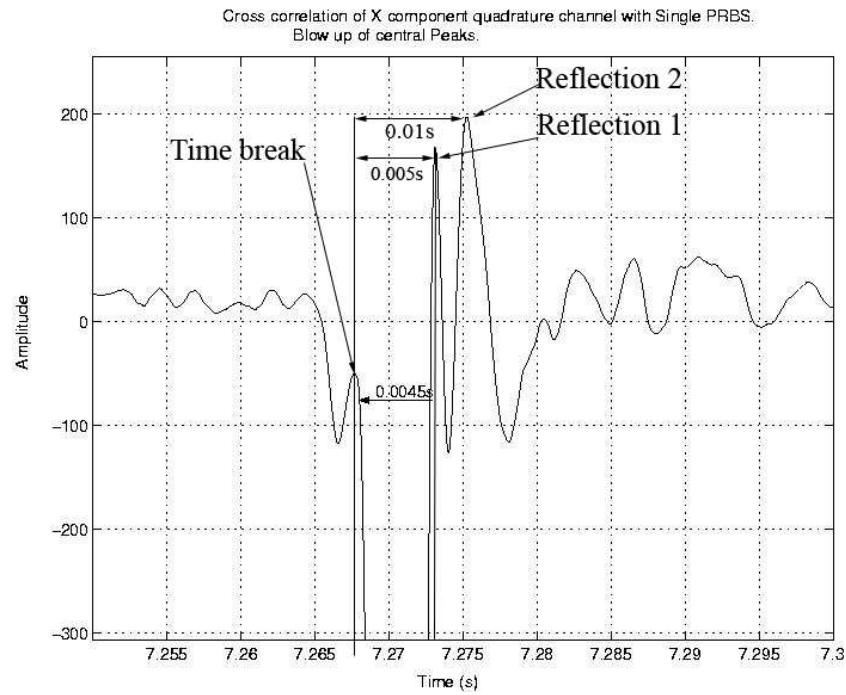


**Figure 4.9:** Main peak width of 4.5 ms is 2.5 times the width of the main peak of the auto-correlation function as shown in Figure 4.8.

At this stage it was decided that both the data processing strategy and the driving strategy were sound and therefore it was time to proceed with experimental testing of the magnetostrictive transducer in the granite block.

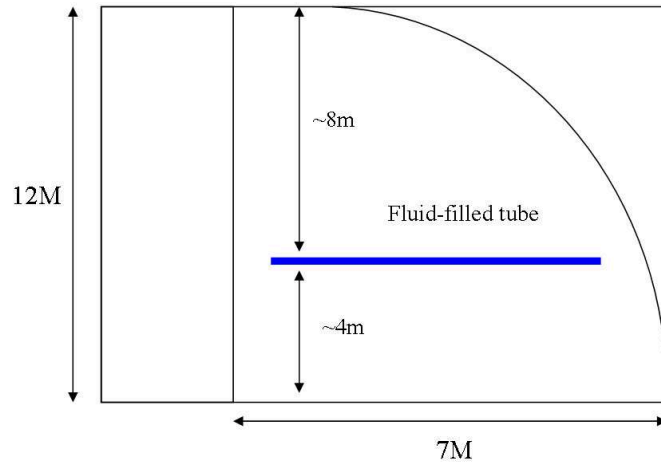


**Figure 4.10:** Plan view of the wave-tank with dimensions.

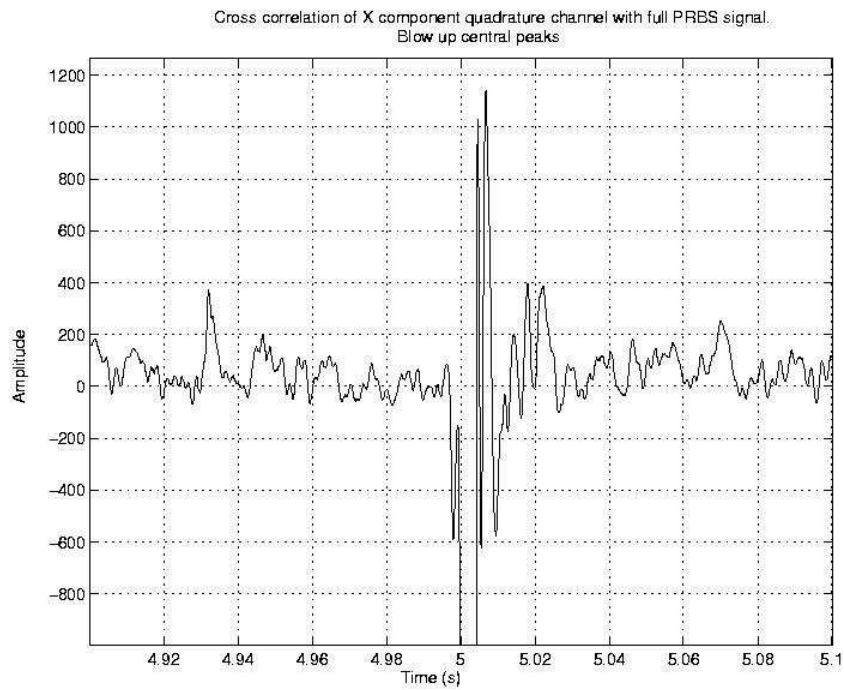


**Figure 4.11:** Cross correlation of full PRBS with received signal showing a 6 times gain to peaks to the right of the main spike, these are interpreted as reflections.



**Figure 4.12:** *Photograph of the wave-tank used for the fluid-filled tube testing.*

## **4.5 Magnetostrictive transducer design and testing in the granite block**

The PRBS signal described in the last section was transmitted to the magnetostrictive source described in the introduction. This was achieved via a power amplifier capable of supplying up to 3A, at voltages up to 200V. This was well within the operation range of the transducer which was peak rated at 8A. The low current is significant in the sequel. The transducer was an off-the-shelf type supplied by Etrema. The material used is a smart material called Terfanol-d this material has the capability to change length by up to 0.001 times its length when subjected to a magnetic field. This would result (for our particular actuator) in a movement of up to  $50\mu m$  under full drive conditions. The mounting arrangement chosen was to hydraulically clamp both ends of the source downhole. The source setup is shown in Figures; 4.13 , 4.14 and 4.15

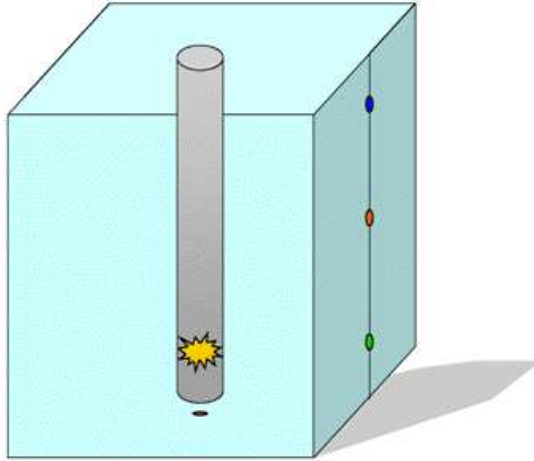


**Figure 4.13:** *Source setup in granite block.*



**Figure 4.14:** *Magnetostrictive source clamped in the granite block.*



**Figure 4.15:** *One of the accelerometers fixed into the block.*

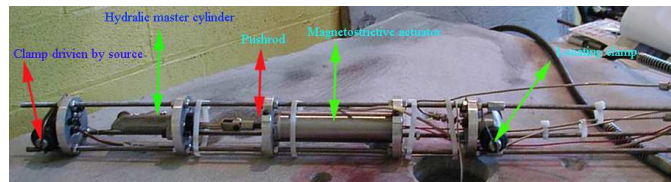


**Figure 4.16:** *Magnetostrictive downhole source.*

The prototype source is shown in Figure 4.16. A pressure test pump was used to pressurize the hydraulic master cylinder to the left of the push-rod in the middle of the photograph. On top of this DC value of pressure an AC value is supplied by the magnetostrictive transducer connected via a push rod to the master cylinder. This pressure signal is simply the same one as was transmitted by the PVDF transducer in the previous model. The signal was conveyed to the walls via a back-to-back pair of brack slave cylinders from a car. These along with an identical pair located at the top of the tool (locating clamp) serve to clamp the tool rigidly to the formation, thereby transmitting the majority of the energy to the formation and not to the bore fluid.

The tool was placed in a 110 mm hole that had been cored in a 5 tonne granite block. Five accelerometers were used; one on the source to record the source signature for further deconvolution; three on the side of the block in an array parallel to the borehole; and one on the base of the block. Figure 4.15 shows one of the block mounted accelerometers.

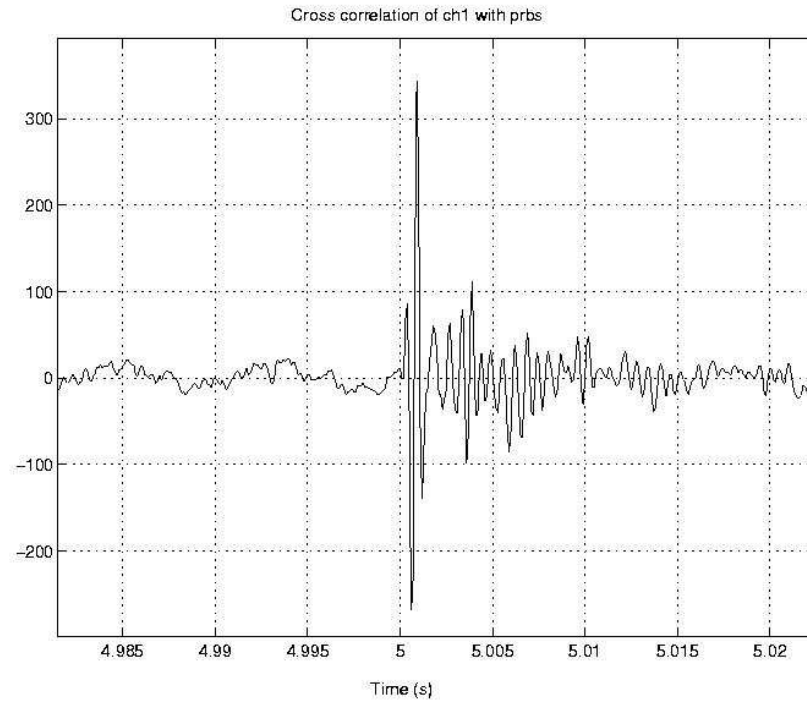


**Figure 4.17:** Result after cross correlation of the recorded source signature with the reference PRBS.

For geophysical applications the major advantage of coded waveforms is the time bandwidth product, the product of the time over which the signal is transmitted and the bandwidth of the signal. For example, a 1 ms pulse with a bandwidth of 1 kHz has a time bandwidth product (TB) of 1. Consider a unique pseudo random binary sequence having a duration of 1 second and containing 1000 binary digits. Each binary digit is, itself, a 1 ms pulse with a 1 kHz bandwidth and the bandwidth of the overall sequence is of the order of 1 kHz. However, since the time duration of the coded waveform is 1s as opposed to 1 ms for the pulse, the TB is 1000. For a given TB the processing gain in dB can be written as  $10 * \log(TB)$  so for a TB of 1000 the processing gain is 30db. Which in principle means that a signal can be sent out at very low power and if the source is run for long enough that signal can be recovered by cross correlation or deconvolution. For example, a signal 20db below uncorrelated noise would be 10db above the noise after recording and processing.

The source signature as recorded by the accelerometer on the tool is shown in Figure 4.17. The data quality is good with a sharp compact wavelet. Figure 4.18 is a recording from the first accelerometer in block, after cross correlation with the PRBS. Despite the fact that this is the

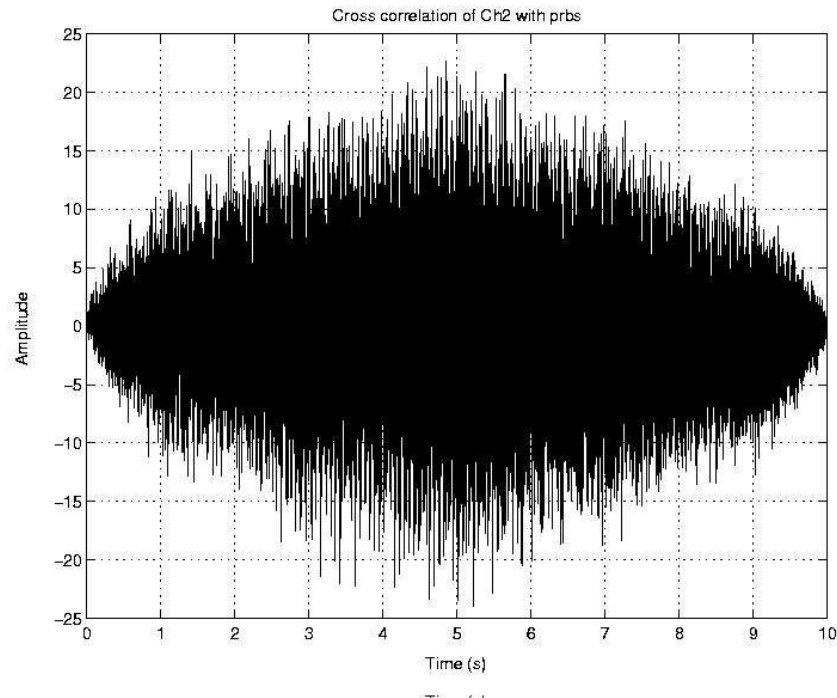


**Figure 4.18:** *The signal recorded by the accelerometer at the top of the block. Run duration was 5s.*

receiver nearest the source, there are no arrivals visible. The time bandwidth product is not great enough to bring the signal up out of the noise.

Figure 4.19 shows the effect of increasing the run time to 20 s. There are now clear correlations emerging from the noise. Each individual peak in Figure 4.19 represents a correlation with the PRBS, the maximum correlation occurs at zero lag, so for a sequence of length 20 s, we expect to see the best correlation at the 20 s point. Figure 4.20 shows this maximum correlation point. The trace is still quite noisy but there is a clear first arrival. This is similar in shape to the source signature shown in Figure 4.17.

Increasing the run time further has a dramatic effect on the data quality. A run time of 80 s greatly improves the resolution on Ch2 and makes it possible to detect an arrival on the accelerometer on the bottom of the block, as shown in Figures 4.21 and 4.22, respectively.

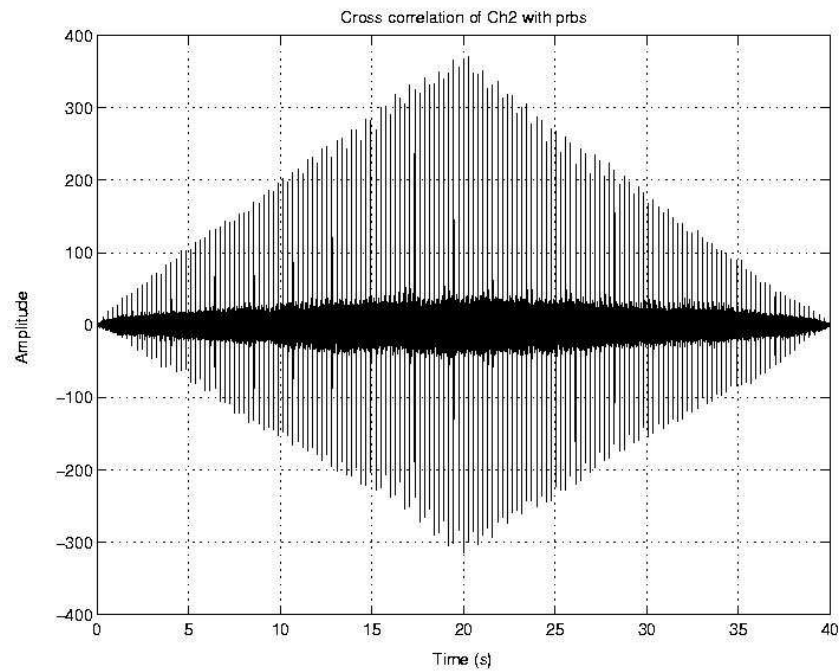


**Figure 4.19:** Data from channel 2; the accelerometer in the block, showing some correlation for a 20 s run.

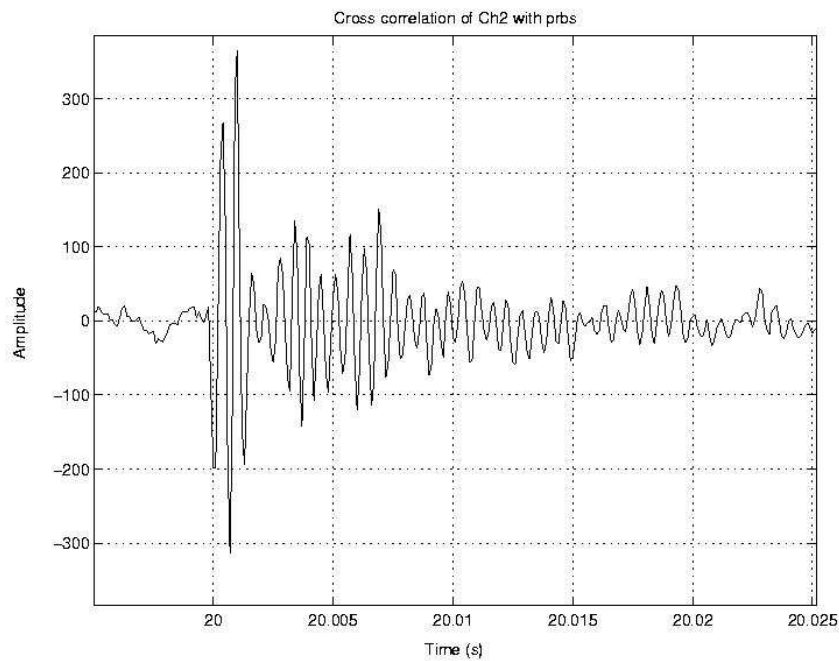


**Figure 4.20:** Result of correlation after a 20s run. This is a blow up of the central peak in Figure 4.19.

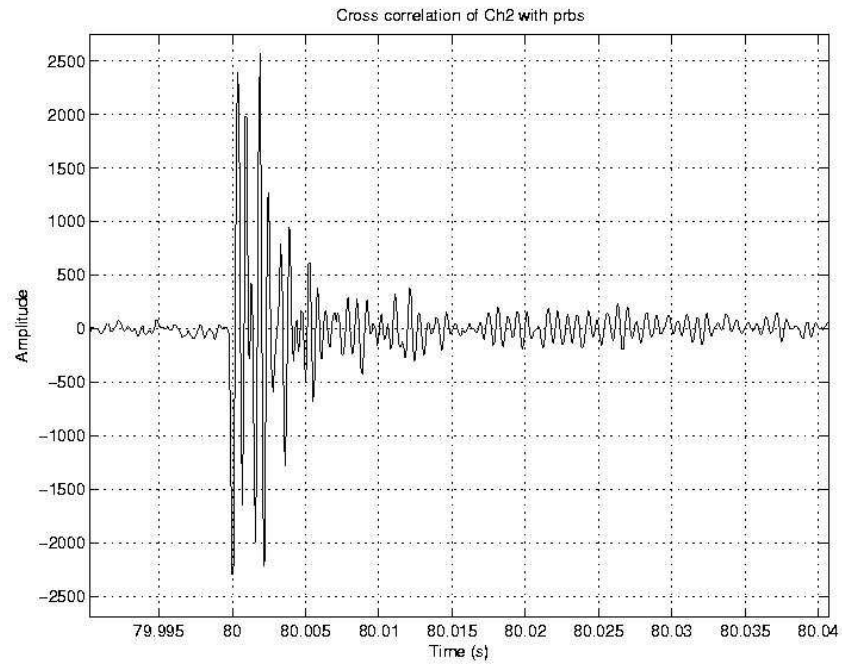


**Figure 4.21:** Result of cross correlation on Channel two, on the side of the block, for a run length of 80s.

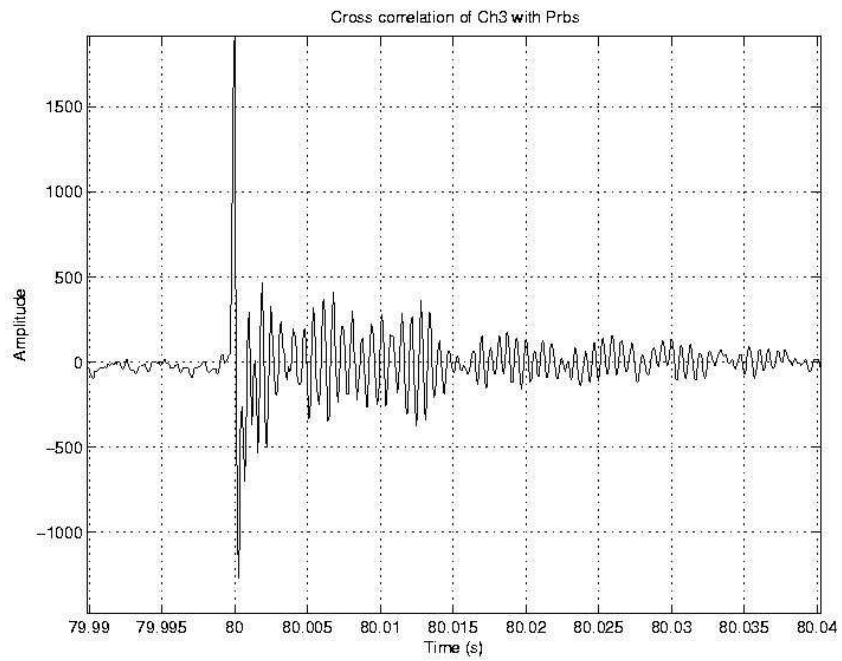


**Figure 4.22:** Result of cross correlation of signal from Channel 3 (bottom of the block, for a run length of 80 s

However, 80 s is an unacceptable duration for one shot in any kind of geophysical survey. The average sweep length for a OVS or land vibrator is closer to 10 s. The reason for the long shot time is due to the inefficiency of the original setup. The key factor was that the push-rod did not have enough freedom to move. This stiffness was related to the surface area of the clamps which, as can be seen from Figure 4.16 was very small. In fact in the cylindrical hole the area that was contacting the wall was of the order of the size of the push-rod diameter or even smaller. This fact meant that full advantage was not taken of any possible hydraulic amplification effects.

An improved design would have pads with a large surface area attached to the clamps, which would have the effect of amplifying the input force and transmitting more energy to the formation, and perhaps also a larger push-rod. The principle at work here is much the same as the hydraulic brakes in a car. The brake pedal, when depressed travels a relatively large distance, and adds a DC modulation to the brake fluid, this force is transmitted to the brake pads which travel a relatively short distance. Because the surface of the brake pads is much larger than that of the push rod a large output force is produced from a relatively small input force. This new design is illustrated in Figure 4.23. This hydraulic amplification can be illustrated as follows: piston  $p$  can move a distance  $L$ , therefore the change in the volume of the fluid is,

$$LA = \Delta V \quad (4.1)$$

where the fluid volume is  $V$ . Consequently the volumetric change is  $\frac{\Delta V}{V}$ , so the increase in pressure will be

$$\Delta P = K \Delta V/V \quad (4.2)$$

where  $K$  is the bulk modulus of the liquid. The pressure acts throughout the fluid and results in a force on the walls of the borehole equal to  $\Delta P a$ , where  $a$  is the cross-section area of the actuator push rod. Note that  $a \ll A$  so the actuator is free to move.

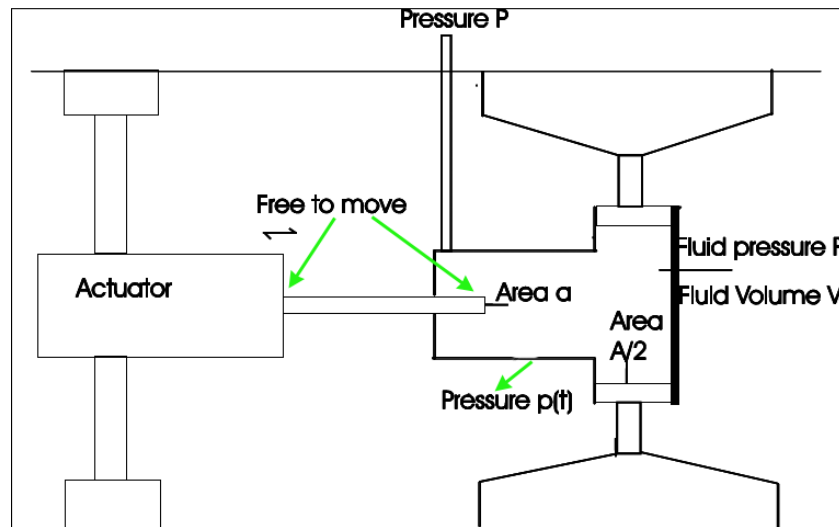


**Figure 4.23:** Schematic diagram of proposed modification to source design.

## 4.6 Conclusions

The results from the testing of the source in the granite block graphically illustrate the large signal strength gains that can be obtained by using the PRBS driving method. It is also noted the no resonance problems were encountered whilst driving the transducer using this method. Despite this, it is apparent that a mechanical redesign of the source is required in order to maximize the potential for hydraulic amplification of the signal. The redesign is necessary to reduce the shot times to a more reasonable length. The aim would be to have shot times of the order of 10s. This would place the source in the same bracket as the current state of the art downhole sources such as the OVS source. The results from this chapter prove that a PRBS driving method can be utilised to overcome the resonance problems associated with magnetostrictive sources, and that it can produce high resolution zero-phase data due to its favorable auto-correlation properties.

The next step in the design of the new source was to find an industry partner that had the expertise and facilities to re-engineer the mechanical aspects of the source and build it into a prototype downhole tool housing. We had many discussions with Baker Hughes Inteq with regard to this, and a draft project plan was drawn up. Unfortunately due to budgetary constraints they were unable to proceed with the project despite being very interested in the concept. At this point all testing of the source was halted, it was agreed that since it was not possible to build and test the source, the next best step would be to model the source in a simple single

well imaging setup. This work is described in the final chapter of this thesis. Despite this setback the new source design is the subject of a UK patent application, and details of the work were presented at the 75th SEG meeting in Houston, Texas.

The next chapter details how the source signature deconvolution method first presented in chapter 2 was applied to the more general case of a marine VSP, and describes a system to collect and process data in real-time whilst drilling. This research is also the subject of a UK patent application.

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# Chapter 5

## First break picking and VSP

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### 5.1 Introduction

In order to drill efficient, accurate wells and hit target prospects drillers need real time information about where the drill bit is located in the subsurface. The conventional way to do this is to use VSP check-shots to place the bit on a surface seismic section. Figure 5.1 shows a standard marine VSP setup and Figure 5.2 shows a land based setup. All the data presented in this chapter was collected using the marine setup. There are a number of problems with the check-shot method. The most significant being, that it cannot be done in real or even close to real time as the whole drill-string has to be removed from the hole to allow the wire-line tool access. This leads to rig downtime and therefore increases costs. One of the first solutions was to put receivers downhole either on a wireline or attached to the drill string, to record the first arrivals from an airgun array. However, these tools can get stuck and retrieval can mean the dismantling of the casing they are therefore a risk to the well. In addition very high noise levels downhole prevent accurate first break picking while drilling, especially when the receivers are not clamped.

A better solution is to build the receivers into the bottom hole assembly (BHA) and to develop a robust algorithm that can pick the first breaks with high accuracy within such a noisy environment. This chapter describes the development of such an algorithm which utilises deterministic signature deconvolution to zero phase the data to make the first breaks easier to pick. This type of deconvolution also improves the resolution of the data and increases the signal-to-noise ratio.

The current state of the art is Schlumberger's SeismicVision tool [22] which can pick the first breaks downhole and transmit them to the surface. However, this tool can only operate during pauses in drilling. This is because of the high noise levels associated with circulation and rotation of the bit. The system outlined in this chapter is a step towards operating in high noise environments while drilling is taking place.

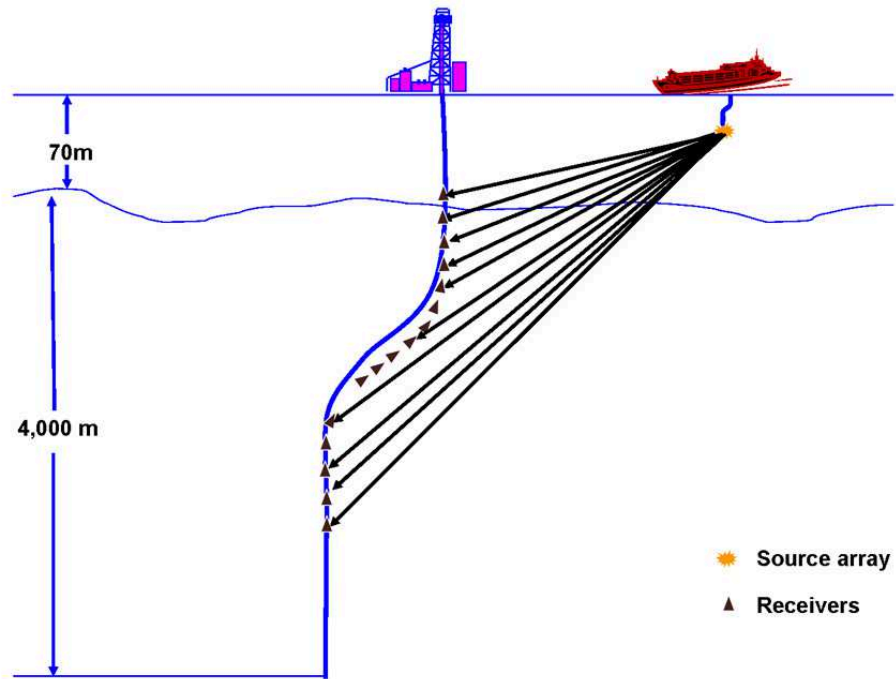


**Figure 5.1:** Marine VSP setup with source deployed from a boat and receivers downhole.

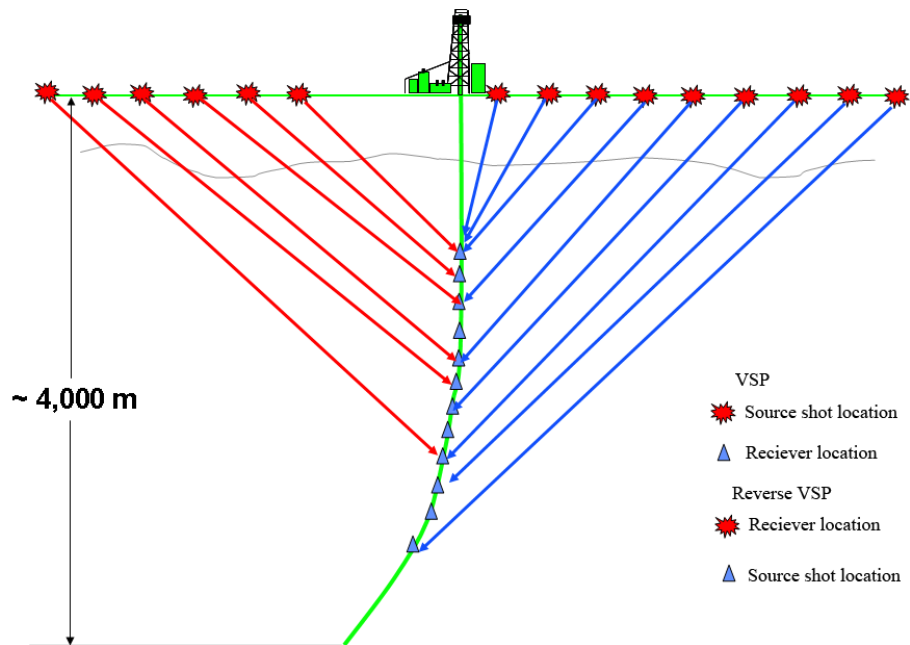


**Figure 5.2:** Normal land based VSP setup with source on the surface and receivers downhole, in a reverse VSP the source positions are replaced by receivers and vice versa.

This chapter is split into six sections: (1) the introduction, including a statement of the problem; (2) a method section which illustrates the steps from a near-field source measurement to a first break pick downhole, (3) a theory section which concisely explains signature deconvolution, (4) presents results obtained with use of the new method, including a comparison of raw data with deconvolved data, illustrating a 1ms accuracy. (5) A short discussion on the results and some recommendations for practical implementations in a downhole tool with a description of how the technique can be used to improve the resolution of VSP data; finally some results from the deconvolution of an entire VSP data-set.

### **5.1.1 The Problem**

The main problem is that high noise levels and the absence of fast telemetry to the BHA (currently telemetry is restricted to 1 bit/s mud pulse) mean that it is not possible to conventionally pick first breaks downhole in real time with any degree of accuracy. This is due in part to the fact that the downhole tool has no knowledge of when the gun fires and what the signature should look like. An additional problem is that only limited information can be transmitted up-hole. These problems exist even during quiet periods, i.e when there is no circulation or pulsing of the mud column and drilling has stopped. What follows is a methodology to overcome these problems by using source signature deconvolution to compress the long oscillatory airgun signature to a compact zero phase wavelet with low side lobe energy. The effectiveness of the technique is illustrated by the results of the deconvolution of both individual traces and a complete VSP record.

## **5.2 Method**

The problem of identifying the first breaks downhole can be approached by using signature deconvolution to compress the wavelet in the data. This works by replacing the long airgun signature with a shorter sharp zero-phase wavelet, which has the effect of shifting the first break from the first departure point of the wavelet to the peak. Since the peak is well above the noise, it is much easier to pick automatically by simply finding the maximum point in an appropriately sized window, as is done in trough to trough picking. Deconvolution to zero phase also improves the resolution, as the zero phase wavelet is the shortest possible wavelet for a given bandwidth [5].

A quality factor could be derived for this result by looking at the ratio of adjacent peaks. For example, if there is a lot of noise or if the deconvolution is poor, the adjacent peaks will be of similar size to the first break. In this case the energy would be spread over a few points in the window, giving a poor quality factor; when the deconvolution works well the energy will be maximised at the first break peak, giving a good quality factor. In order to perform the deconvolution it is essential to measure the airgun signature for every shot. This gives a description of what the wavelet looks like in the near field. This information, along with knowledge of the source and receiver geometry, can be used to construct a far-field wavelet.

The far-field signature differs from the near-field signature in the relative amplitudes of the direct arrival and the arrival reflected from the sea surface. In the near field the direct arrival has a much higher amplitude than the reflected arrival, as shown in Figure 5.3. In the far-field the path lengths of the direct and reflected waves are similar. This means that both signals are attenuated by a similar amount due to spherical divergence and the amplitude of the direct wave matches the amplitude of the reflected wave. Once the receiver is in the far-field the shape of the signal does not change significantly. This is only true if the source array has little or no directivity, which is the case for the small arrays used in normal VSP surveys.

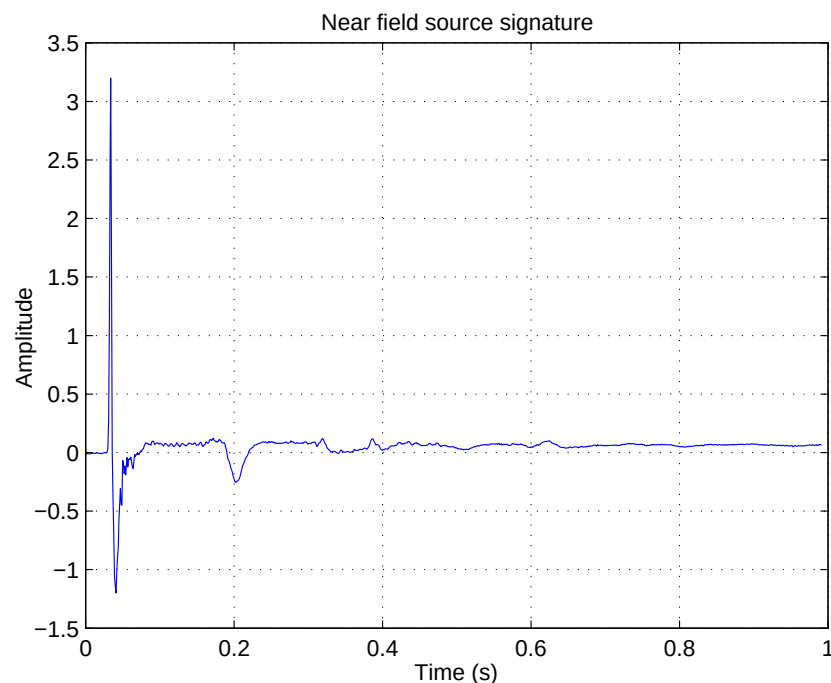


**Figure 5.3:** Source signature recorded 3.5m away from array.

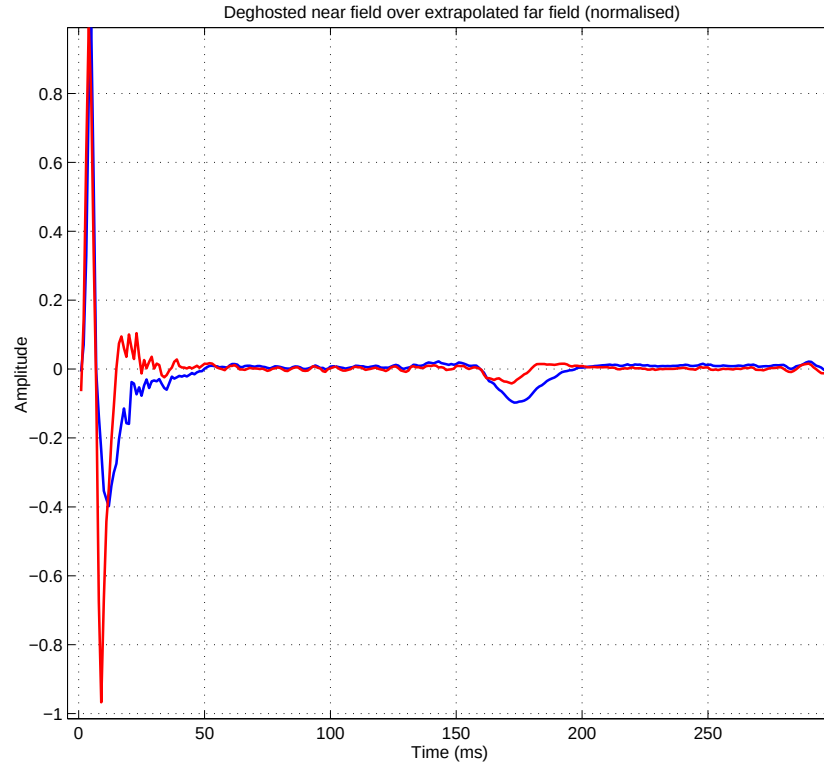


**Figure 5.4:** *Near field source signature with sea surface ghost removed (blue) over extrapolated far-field signature.*

If the geometry of the near field receiver and the guns is known, the far field signature can be very accurately predicted from the near-field measurement. In order to do this, it is necessary to obtain the direct wave uncontaminated by the sea surface reflection. If the geometry is known, the reflection can be calculated and subtracted from the near field measurement to leave the direct wave. The extrapolation to the far-field is then simply the addition of the appropriately scaled reflection in the right place as described in the theory section, and as shown in Figure 5.4 This can all be done downhole if a recording of the near field signal is available, as it is not necessary to know the position of the downhole receiver or the velocity structure downhole, because the shape of the wavelet is the same everywhere in the far-field.

Once the far-field signature is known, the next step is to design an optimum deconvolution filter to compress it to a zero-phase wavelet. An important point here is that the zero-phase wavelet needs to have an amplitude spectrum similar to that of the original signature. This is to ensure that the increase in resolution obtained by the deconvolution step is obtained without a decrease in signal-to-noise ratio. This is achieved this by fitting a smooth curve to the amplitude

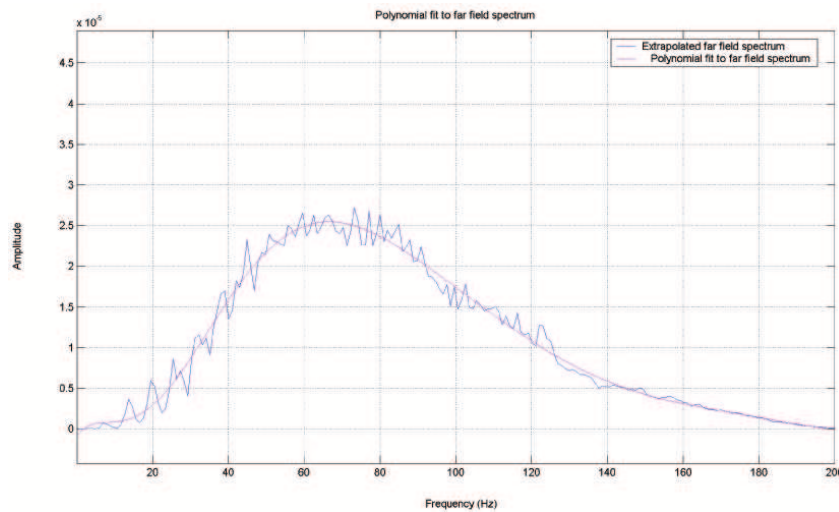


**Figure 5.5:** Smooth 10th order polynomial fit to far-field amplitude spectrum.

spectrum of the far-field signature up to the first null due to the ghost, as shown in Figure 5.5. This 'ghost' is the direct wave reflected from the sea surface, and because it has the opposite polarity to the direct wave it interferes destructively. This results in a null in the spectrum. The zero phase wavelet is then created by transforming the smoothed amplitude spectrum with zero phase back to the time domain as shown in Figure 5.6.

A shaping filter is used to find the deconvolution filter which converts the long airgun signature to the zero phase wavelet. On input of the far field signature, the algorithm finds a filter which minimises the least squares error between the input and the desired output. This filter is the deconvolution filter for this shot. The actual deconvolution of the data is done by convolving this filter with the recorded signals for that shot. If there are shot-to-shot variations a new filter needs to be calculated, but the desired output always stays the same to ensure the wavelet stays the same after deconvolution throughout the whole data-set.

There is an additional problem here. It is possible that over the course of a survey the gun signatures may change significantly for example, one gun might drop out of the array or the array may be moved. This change needs to be communicated to the downhole tool. There are two solutions to this problem. The more conventional and, to an extent, more limited solution is to have a library of signatures downhole, with the same library up-hole. The measured signature could be compared up-hole to the library signature in use downhole. When the RMS error between the signatures is over some threshold, say 5%, the next best signature could be

found up-hole and then a pulse could be sent downhole to tell the tool to use the corresponding signature. This method is only as good as the signature library; and a decision would need to be made on the extent of the library based on actual field experience of the variability of the airgun signature, field conditions, and the amount of storage available downhole.

A much better option is to compute the shaping filter up-hole for every shot and transmit the filter coefficients downhole. By doing this any type of signature variation can be accounted for and removed to ensure the best results for every shot. However, due to the bandwidth constraints of mud pulse telemetry, this is not currently feasible without compressing the filter coefficients. The library method as described in the previous paragraph is currently being commercialised by Baker Hughes Inteq. It is anticipated that once the telemetry bandwidth increases, then it will be possible to operate the system using a compressed transmitted signature. The processing steps of the algorithm are outlined in the flow chart as shown in Figure 5.7.

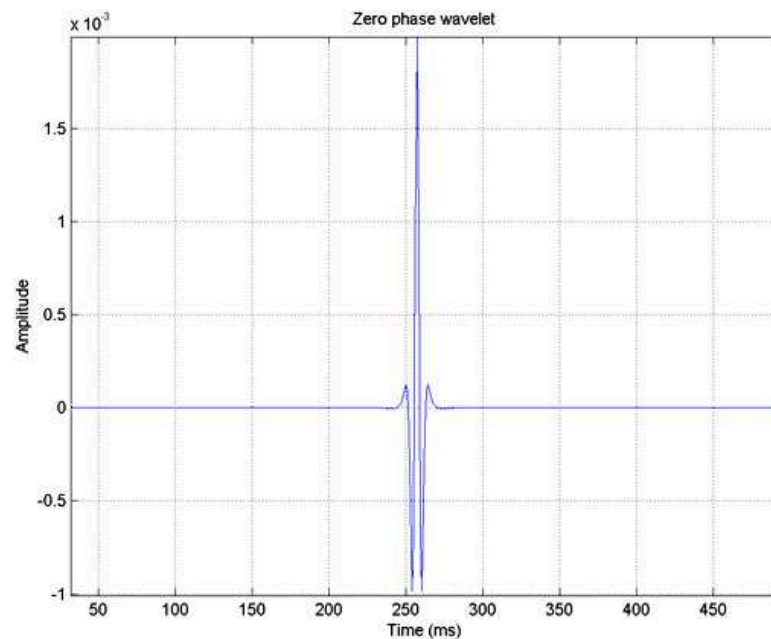


**Figure 5.6:** Zero phase equivalent from polynomial fit to far-field spectrum, used as desired output for shaping filter.

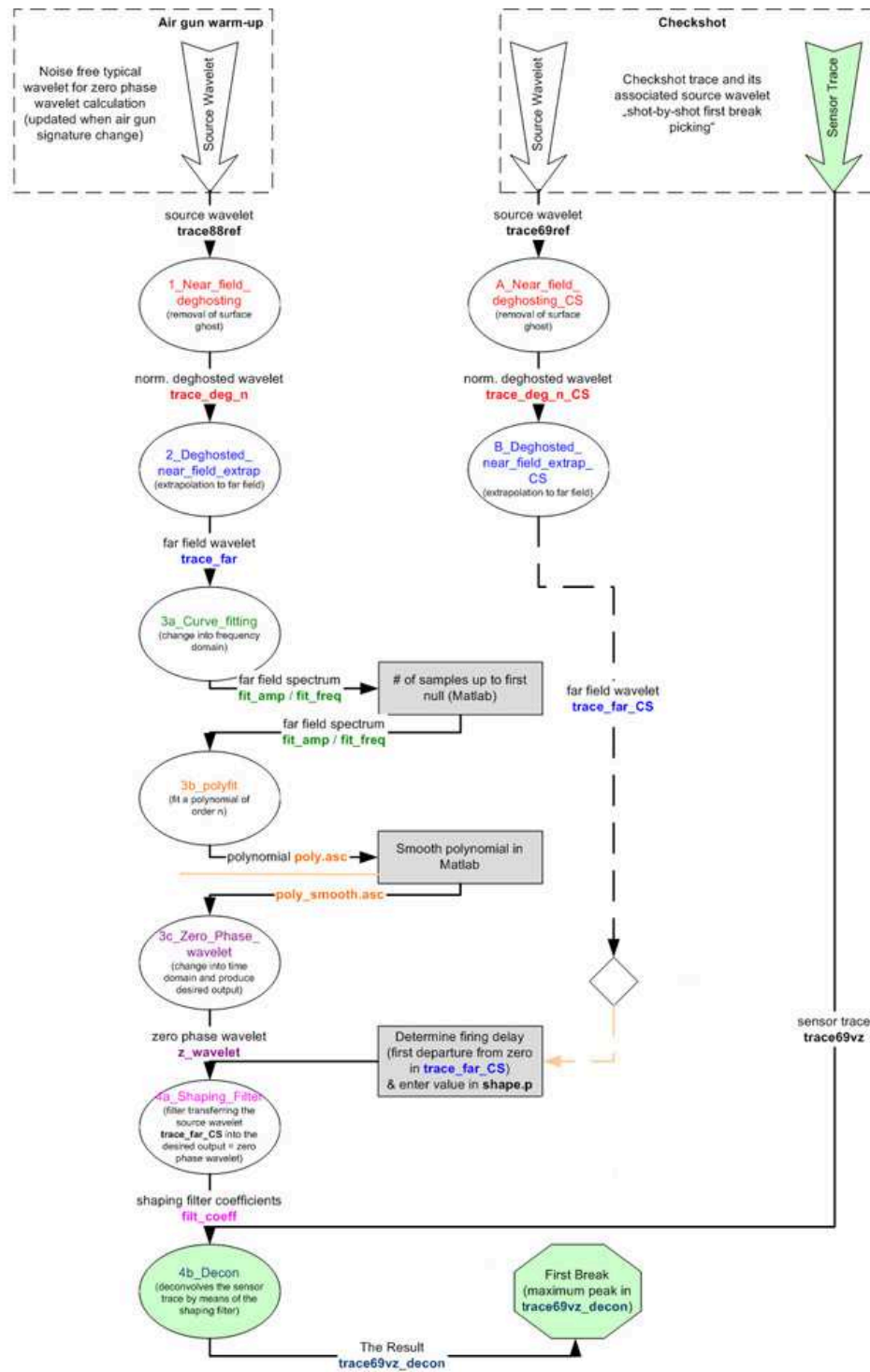


**Figure 5.7:** Flow chart describing the processing steps for VSP deconvolution.

### 5.3 Theory

#### 5.3.1 Removal of the source ghost in the time domain

The data recorded on the near field hydrophone mainly consist of two components: a direct wave, which travels directly from the source, and a wave reflected from the sea surface, as shown in Figure 5.8. The direct wave uncontaminated by this reflection, or ghost as it is known, is required.

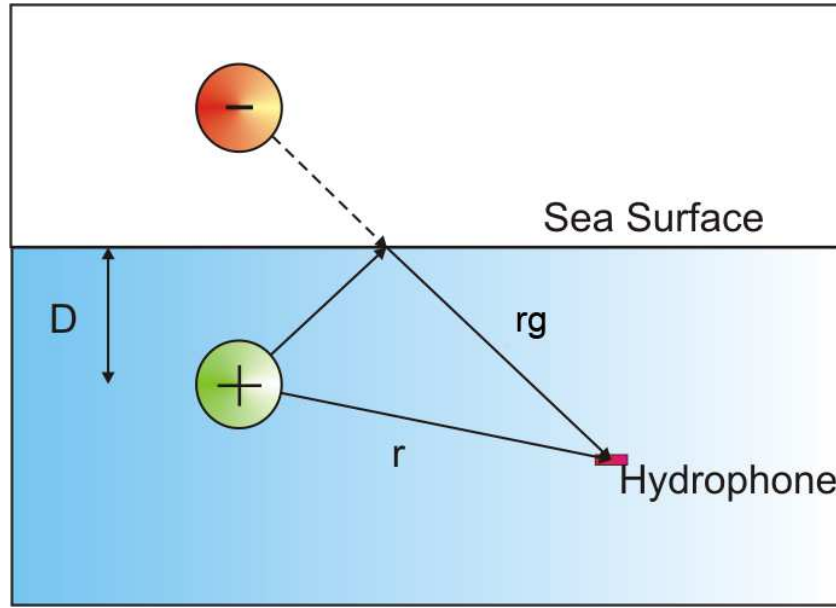


**Figure 5.8:** The virtual source method of calculating  $rg$  the distance traveled by the reflected wave, after Ziolkowski [86].

The total pressure at the hydrophone 1m from the gun is following Ziolkowski [86]

$$p(t) = \frac{V_p(t)}{h} = \frac{1}{r} s\left(t - \frac{r}{c}\right) - \frac{1}{rg} s\left(t - \frac{rg}{c}\right) \quad (5.1)$$

In which  $V_p(t)$  is the recorded signal,  $s(t)$  is the source signature, and  $h$  is the sensitivity of the hydrophone,  $r$  is the distance between hydrophone and the centre of the rising bubble and  $rg$  is the distance between the hydrophone and the center of the sinking virtual bubble. The second term in Equation 5.1 for the pressure at a time  $t$  anywhere in the water, is the ghost; the direct wave from the airgun can be obtained by rearranging the equation.

Then

$$s\left(t - \frac{r}{c}\right) = rp(t) + \frac{r}{rg}s\left(t - \frac{rg}{c}\right). \quad (5.2)$$

Which leads to an equation for  $s(t)$ , the direct wave uncontaminated by the ghost,

$$s(t) = rp\left(t + \frac{r}{c}\right) + \frac{r}{rg}s\left(t - \frac{rg - r}{c}\right) \quad (5.3)$$

After deghosting it is necessary to normalise the signal to 1m by multiplying the deghosted signal by  $r$ , the distance traveled by the direct wave.

### 5.3.2 Removal of the source ghost in the frequency domain

Removal of the ghost is much more efficient in the frequency domain using the Fourier transform. The convolution theorem states that convolution in the time domain is equivalent to multiplication in the frequency domain, and vice versa.

Equation 5.1 for the total pressure at a location in the water can be written as a convolution:

$$p(t) = s(t) * \left\{ \frac{1}{r}\delta\left(t - \frac{r}{c}\right) - \frac{1}{rg}\delta\left(t - \frac{rg}{c}\right) \right\} \quad (5.4)$$

Using the Fourier transform

$$S(\omega) = \int_{-\infty}^{\infty} s(t) \exp\{i\omega t\} dt, \quad (5.5)$$

and the convolution theorem, Equation 5.4 in the frequency domain is

$$p(\omega) = S(\omega) \left[ \frac{1}{r} \exp\left\{i\omega \frac{r}{c}\right\} - \frac{1}{rg} \exp\left(i\omega \frac{rg}{c}\right) \right] \quad (5.6)$$

rearrangement yields the normalised direct wave, in the frequency domain  $S(\omega)$ .

$$S(\omega) = \frac{P(\omega)}{\left[ \frac{1}{r} \exp \left\{ i\omega \frac{r}{c} \right\} - \frac{1}{rg} \exp \left\{ i\omega \frac{rg}{c} \right\} \right]} \quad (5.7)$$

This is the deghosted near field recording, where  $r$  and  $rg$  are the respective distances from the actual and virtual source to the near field hydrophone. This deghosted near field recording can be used to create a synthetic far field signature. If the far field signal were measured it would consist of the direct arrival from the source followed by the reflected arrival from the sea surface, or the ghost. This signal can be generated by substituting  $S(\omega)$  into equation 5.6, we need to redefine two new distances  $r_f$  and  $rg_f$  the distances from the hypothetical far field phone to the source and virtual source respectively. Equation 5.6 then becomes

$$p_f(\omega) = S(\omega) \left[ \frac{1}{r} \exp \left\{ i\omega \frac{r_f}{c} \right\} - \frac{1}{rg} \exp \left\{ i\omega \frac{rg_f}{c} \right\} \right] \quad (5.8)$$

$r$  and  $rg$  as before are the respective distances to the near field phone. This yields  $p_f(\omega)$  the pressure in the far field. Essentially we are taking the deghosted near field signal scaled by the distance from the source and the virtual source and applying a phase shift  $\exp \left\{ i\omega \frac{r_f}{c} \right\}$  which creates the direct wave in the far field, another phase shift  $\exp \left\{ i\omega \frac{rg_f}{c} \right\}$  creates the ghost in the far field, which has a negative sign due to the -1 reflection coefficient of the sea surface. The far field signature  $p_f(\omega)$  is then simply the addition of these two phase shifted direct waves.

### 5.3.3 Wiener filtering

Wiener filtering involves the design of a filter so that error energy between actual and desired outputs is a minimum. The error energy is defined as

$$L = \sum_t (d_t - y_t)^2 \quad (5.9)$$

The output,  $y$  is the convolution of the input,  $x$  with the filter,  $f$ , so

$$y_t = \sum_{\tau} f_{\tau} x_{t-\tau} \quad (5.10)$$

Substituting Equation 5.10 into Equation 5.9 gives,

$$L = \sum_t \left( d_t - \sum_{\tau} f_{\tau} x_{t-\tau} \right)^2 \quad (5.11)$$

The goal is to compute the filter coefficients  $(f_0, f_1, \dots, f_{n-1})$  so that  $L$  is a minimum. The filter length must be defined at the start. This is in practice chosen by trial and error. Equation 5.11 can be converted to matrix form [76]

$$\begin{bmatrix} r_0 & r_1 & r_2 & \cdot & \cdot & \cdot & r_{n-1} \\ r_1 & r_0 & r_1 & \cdot & \cdot & \cdot & r_{n-2} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ r_{n-1} & r_{n-2} & r_{n-3} & \cdot & \cdot & \cdot & r_0 \end{bmatrix} \begin{bmatrix} f_0 \\ f_1 \\ \cdot \\ \cdot \\ f_{n-1} \end{bmatrix} = \begin{bmatrix} g_0 \\ g_1 \\ \cdot \\ \cdot \\ g_{n-1} \end{bmatrix} \quad (5.12)$$

Here  $r_i$  is the coefficient in the auto-correlation of the input signal  $x_t$  at lag  $i$ ,

$$r_i(i) = \sum (x_t)(x_{t-i}) \quad (5.13)$$

$g_i$  is the coefficient in the cross correlation function between the desired output  $d$  and the input  $x$  written as,

$$g_i = (d \star x) = \sum_x (d_t x_{t+j}) \quad (5.14)$$

Determination of the Wiener filter coefficients involves the solution of the normal equations. the matrix is symmetric and Toeplitz and can be solved by Levinson recursion [46], an operation that reduces the computation operations from  $n^3$  to  $n^2$ . This involves computation of a two-point filter, from which a three-point filter can be derived, and so on, until the  $n$  point filter is derived [76].

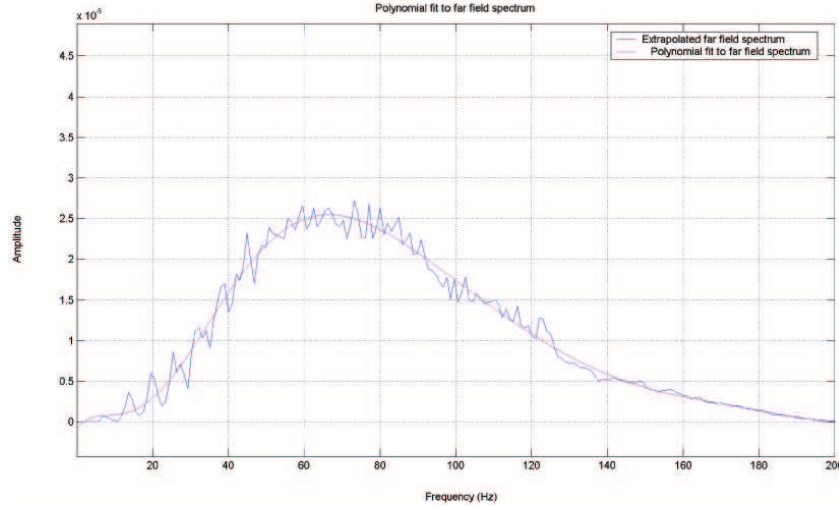


**Figure 5.9:** Smooth zero phase wavelet spectrum over extrapolated far field spectrum.

### 5.3.4 Signature deconvolution

The aim of the signature deconvolution is to take the long airgun record in Figure 5.3 and convert into the shortest possible wavelet with the same bandwidth. This is achieved by converting the source wavelet - which is present in all the data for that shot to a zero-phase wavelet [5]. This has the effect of moving the first-break to the peak of the first arrival, rather than the first departure from zero, thus making it easier to detect in the presence of noise. The filter which converts the source signature to the zero phase wavelet is convolved with the data recorded for that shot; this has the effect of making the all the signatures in the data zero phase. For a perfect deconvolution all events other than noise would be zero phase wavelets therefore maximising the resolution. The noise may be attenuated later by stacking.

Figure 5.9 shows the smooth amplitude spectrum of the wavelet over the spectrum of the source. The zero phase wavelet that has this amplitude spectrum is shown in Figure 5.6. This is the wavelet that formed the basis of the signature deconvolution. It is therefore important to try and make it as sharp as possible with minimum side lobes, as large side lobes will cause ringing in the data. It appears that the smoother the spectrum the smaller the side lobes. Any large increases in slope in the frequency domain translates to large side lobes and ringing in the time domain.

The aim is now to take the computed far field signature  $p_f(t)$ , and find a filter that converts it to the shorter zero phase wavelet,  $d(t)$  in Figure 5.6. Let the filter be  $f(t)$ . The operation

performed is the convolution:

$$p_f(t) * f(t) = d(t). \quad (5.15)$$

$f(t)$  can be found by solving a least-squares problem using the Wiener normal equations, with  $p_f(t)$  as the known input and  $d(t)$  as the desired output. However, in this case, it is more efficient to transform the operation to the frequency domain so that the convolution becomes a multiplication as shown in Chapter 3. Once the data has been deconvolved to the same zero phase wavelet, all shot to shot variations should be eliminated, it is therefore possible to stack consecutive shots at the same depth

## 5.4 Results and discussion

Figure 5.10 is the result of convolving the shaping filter with the computed far-field signature. This resembles very closely the desired signal in Figure 5.6 which is an important first check in

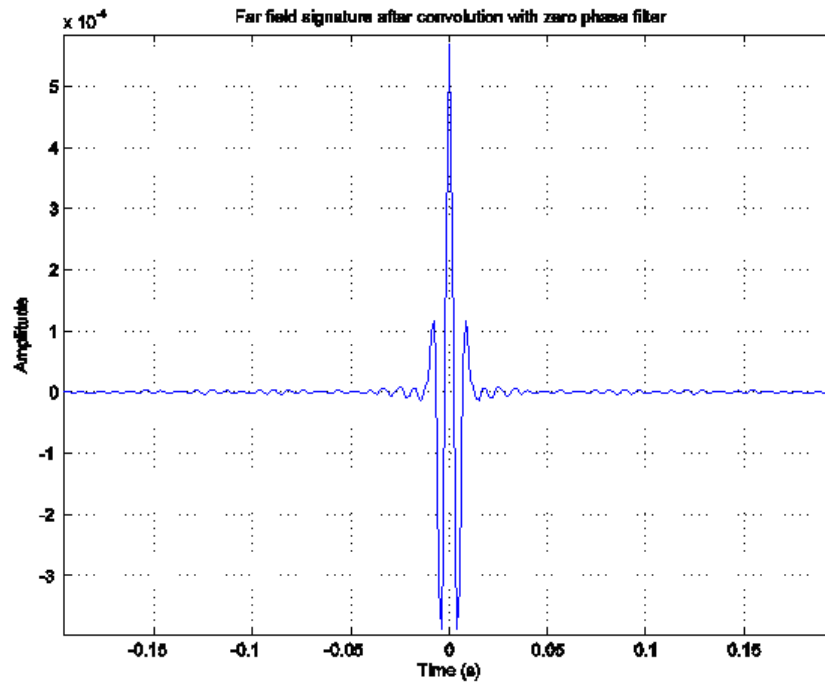


**Figure 5.10:** Output from zero phase shaping filter.

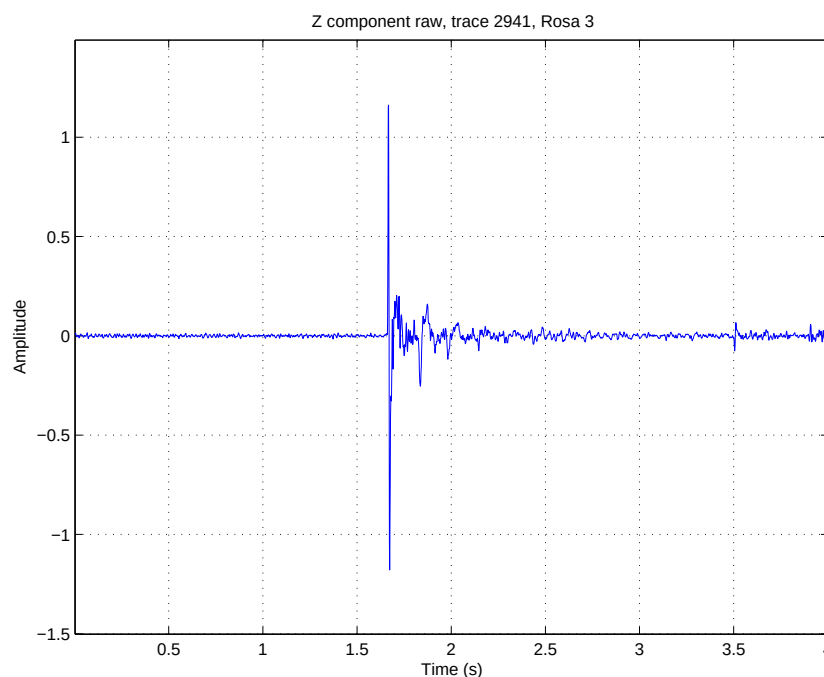


**Figure 5.11:** *Raw trace to be deconvolved, showing good first arrival.*

the process and provides assurance that the result of the deconvolution will be correct because the filter is performing as expected.

An example of the raw data recorded downhole is shown in Figure 5.11; this comes from the vertical component of a triaxial clamped geophone placed downhole, recorded during a marine VSP survey. The source was a airgun array consisting of four 150 cu. in. guns, mounted on a H-rack, with a near field hydrophone placed 3.5 m under the guns and equidistant to each gun. The wave shape of the first arrival in Figure 5.11 very closely matches the derived far-field signature, shown as the red trace in Figure 5.12. The arrival at 1.84s is the first bubble pulse. The result of convolving the shaping filter with the trace is shown in Figure 5.12. The characteristic far-field shape has been transformed to closely resemble the desired zero-phase wavelet shape and the bubble pulse at 1.84s has been removed. This illustrates the compression of the long pulse to the shorter zero phase wavelet. This increase in resolution has also uncovered another arrival at 1.725s that was not seen on the raw trace.

Figure 5.13 is a blow up of the first break. This shows the peak of the deconvolved trace overlying the first departure from zero of the raw trace. Figure 5.14 shows the exact location of the peak of the deconvolved trace extrapolated with respect to the conventional first break of the

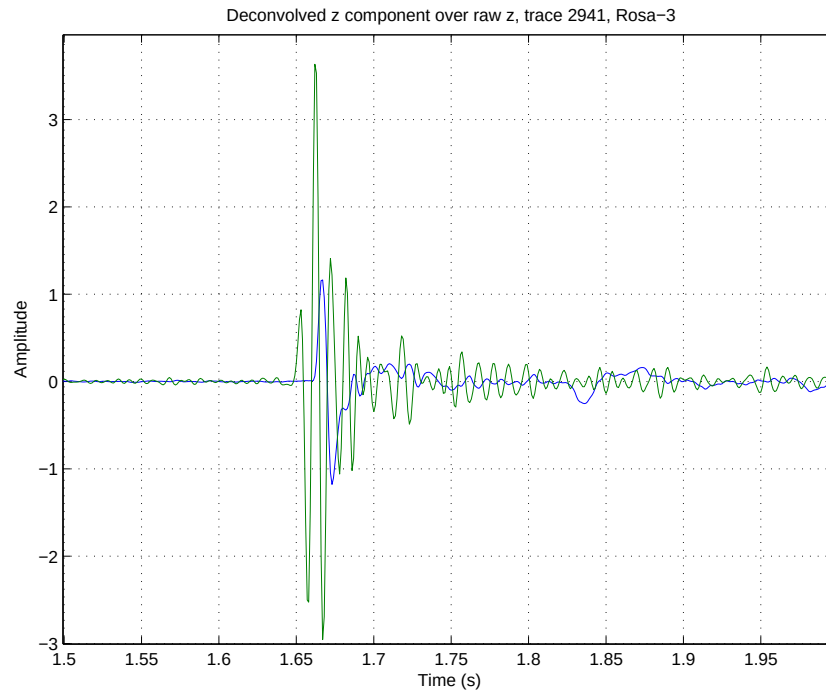


**Figure 5.12:** Result of zero phase deconvolution (green) displayed over raw trace (blue).

raw trace. This illustrates how zero phase deconvolution makes the first break much shorter and therefore easier to pick. Also, because the signature present in the data has been compressed to a shorter sharper zero-phase wavelet, the resolution is effectively increased, since events which formally overlapped are now separated and discernible. The shortness of the wavelet is a direct consequence of the smoothness of its amplitude spectrum.

## 5.5 Practical considerations

It is important to consider how the system will work in practice and how the tool will function while downhole. The major problem is that the tool's only telemetry is low bandwidth mud pulse (1 bits/s). So it has to be able to function with very little instruction from the surface. In order to do the deconvolution and the first break picking the tool needs to know what the source signature is and the source and receiver geometry. This should vary by only a few cm once the equipment is deployed. The coordinates can easily be transmitted downhole before drilling or firing begins. If for any reason the array moves, then the coordinate can be retransmitted perhaps while the guns are warming up.

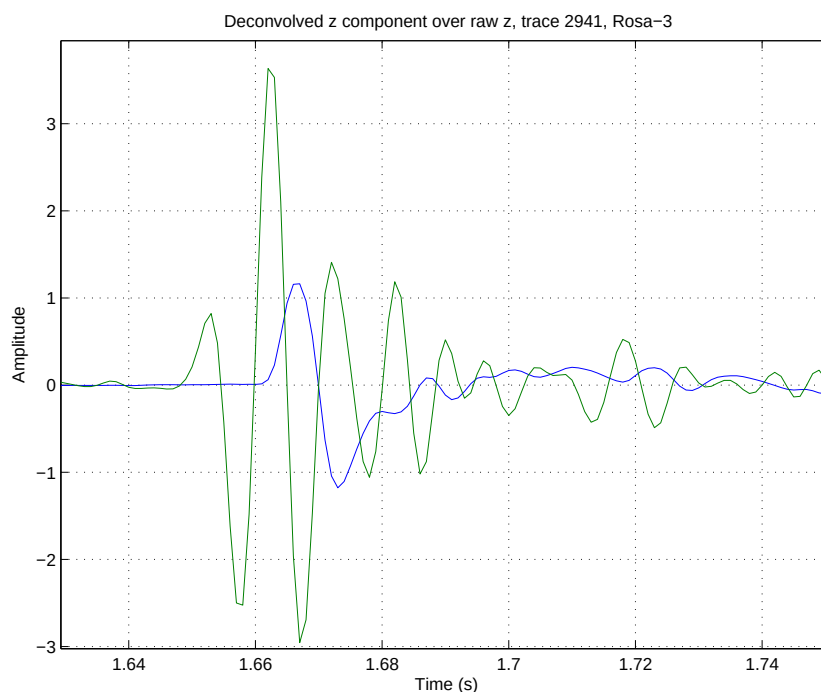


**Figure 5.13:** *Blow up of first break, note similarity of deconvolved arrival (green trace) to zero phase wavelet.*

The source signature itself presents a problem. It is possible to produce a very repeatable source signature once the guns are warmed up, but with small arrays the signature can vary. Large towed arrays are much more repeatable, but are only employed for large scale surface surveys with hydrophone streamers. One solution is that the source signature be measured for every shot, and that the downhole tool has a library of possible source signatures preferably taken from source tests. The same library should be present up-hole. The best library signature for the particular field set should be selected, and then the tool instructed to use this signature by sending a sign bit downhole by mud pulse.

Then the difference between the library signature and the recorded signal (from the near field hydrophone) is computed uphole. A filter can then be designed up hole that makes the library signature look like the measured signature. The coefficients of this filter could then be compressed and sent downhole and convolved with the library signature, enabling the tool to modify the library signature to exactly match the real source signature. Ensuring that the tool will have the correct signature for every shot and if any shot-to-shot variations are present they will be removed by the deconvolution.

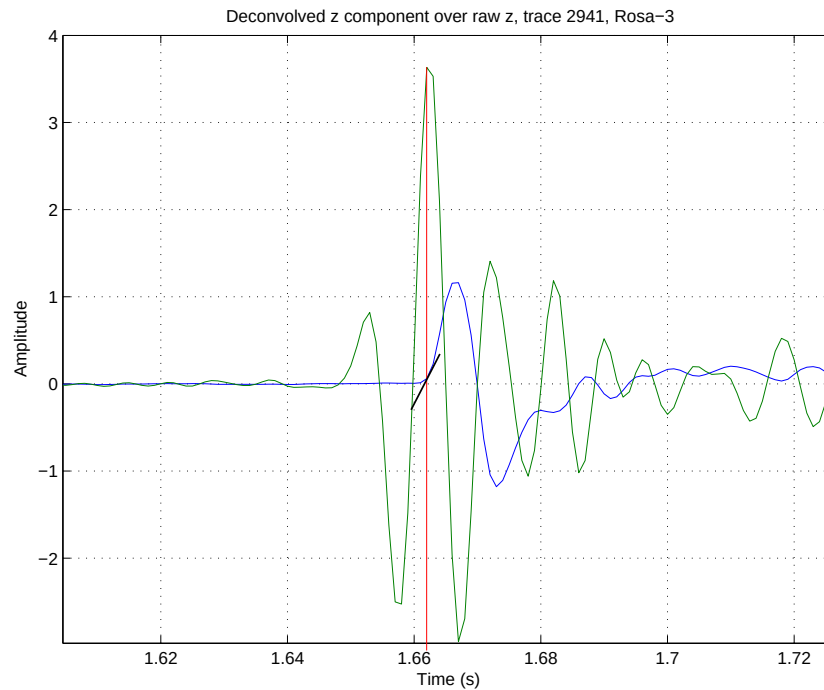


**Figure 5.14:** *Overlay of raw and deconvolved traces red line indicates first break time on zero phase trace. Black line indicates conventional first break pick on raw trace.*

This solution combines the efficacy of the library concept with the robustness and accuracy of source signature deconvolution. Therefore if the signature is known for every shot, repeatability is no longer a major issue, although it is preferable that the changes between signals are not very large, or it would take too long to transmit the information downhole. Changes in gun size or even array type can be accommodated simply by switching to a more appropriate library signature. Eliminating shot-to-shot variations means that the traces could be stacked downhole with the confidence that this is not introducing artifacts into the data. These stacked traces could then be compressed and transmitted up-hole, further reducing the transmitted data volume.

Perhaps the most important consideration of all is timing. It is essential that the up-hole and downhole clocks are synchronized and do not drift outside a predefined range. We understand from private discussions with Baker Hughes Inteq personnel that clocks with the required accuracy are available. The problem then becomes if the tool is listening continuously how will it know to start recording at the right time. The solution is to keep the time between air-gun shots almost constant.

The tool should be continually listening and deconvolving, and the first break picker should

also run continually. While the array is not firing there could be some noise peaks that appear and the tool may misinterpret these as first breaks. The key is to make sure the tool only starts recording and transmitting data when these first break peaks recur at a constant time interval (in practice there would be some error bounds, e.g.  $\pm 100\text{ms}$ ). Once two or three peaks arrive, all separated by the shot interval, the tool treats these as a signature and knows to start recording. It can then send the first break times up-hole along with a quality factor, derived from the ratio of the first break peaks to adjacent noise peaks and the time interval between the first breaks. Once these times are received and the quality factor is high then the tool can obtain the transit time for the direct waves.

The times transmitted up-hole will be the absolute times, i.e starting from when the source was synchronised at the surface. The length of time the source has been downhole the time instants when the airguns have fired (from time breaks on the guns preferably, or from the near field hydrophone), are known, so the method would be to subtract this delay from the transmitted time to give the time of the first break. Accuracy could be improved by utilising finer sampling on the time break sensor, and downhole.

## **5.6 VSP deconvolution**

The system developed here for the first break picking of data downhole can also be used to reprocess new or existing VSP data, providing that the geometry of the near field hydrophone is known and the quality of the source signature recording is good. The results of applying source signature deconvolution to a complete VSP data-set is discussed in this section along with an illustration of how the method differs from another method called source signature deconvolution or deterministic deconvolution.

Source signature deconvolution is routinely employed to improve the resolution of VSP data. Its usefulness is understood and accepted, but the correct method of application is rather less well understood. The processing steps known as source signature deconvolution and VSP deconvolution are described below. In the first instance the signature from the near field hydrophone is recorded and a filter is found that converts this to a desirable wavelet, generally zero-phase. This filter is then convolved with the recorded data, with the belief that this will replace the source signature with the desired wavelet. This cannot be the case as the signal received at the geophones is significantly different in shape from the near field signature. This

is obvious from a cursory inspection of the data. A filter which converts the near field signal to a desired wavelet will perform poorly on data recorded in the far-field, with the result that the first break will be incorrect.

Figure 5.15 is a trace from a marine VSP data-set, which has been deconvolved using the near field source signature in place of the far-field signature, and using a four point desired wavelet. The amplitude of the desired wavelet is zero at 4.0 Hz and increases linearly up to 8.0 Hz, it is flat from 8-80.0 Hz, and then decreases linearly to zero at 96.0 Hz. This is an industry standard way to construct a desired wavelet, and would normal be referred to as a four point wavelet with corner frequencies of 8.0, 8-80 and 96 Hz. The filter does an apparently good job of sharpening up the first arrival, but it seems to introduce an artifact at around 1.55 s before the first arrival and there are no clear events after the first break. Comparison with the properly deconvolved trace in Figure 5.13 shows the wavelet shape has not changed significantly, it does not look like a zero-phase wavelet. Comparison with the raw data in Figure 5.11 shows that the first break (taken to be the first significant peak) is in error by 10 ms. In this case a near field signature

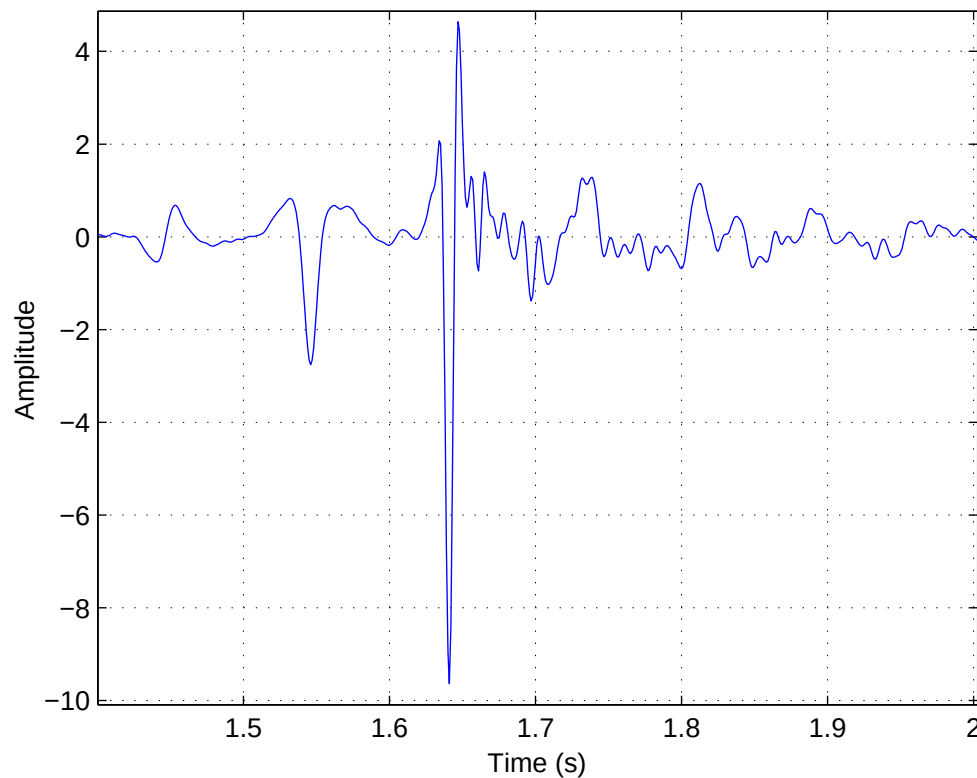


**Figure 5.15:** *The result of deconvolving the raw trace with the near field deconvolution filter.*

and a raw signature from the same shot were used, so this is a best case scenario.

VSP deconvolution is described in detail by Ross et al. [65]. It uses a source signature extracted from the VSP data itself, after it has been separated into up and down going wave-fields. In general the down going P-wave-field is used, a move out correction is applied and the traces are stacked. An arbitrary window is then chosen around the first break and the wavelet inside this window is said to represent the source signature. It is well known that the source signature can vary considerably over the course of a VSP survey, due to towing depth, gun leakage and weather conditions. In this method, if any variations are present, they will be irretrievably mixed together resulting in a wavelet which bears little resemblance to the true signature for each shot. Again a filter which converts this signature to a desired wavelet will have unpredictable results on the different wavelets present in the data and could introduce artifacts which may result in an incorrect first break pick. If the signature changes, the effect will be different on every trace. This lateral change in wavelet shape could be incorrectly attributed to the geology.

The correct approach is to use the near field signature to construct the far field signature and use this to construct a deconvolution filter, as per the theory and method already outlined in Section 5.3. The results presented here have been obtained by deconvolving a marine VSP data-set on a shot-by-shot basis, i.e a separate deconvolution filter was computed for each shot and applied to the data from that shot, and so on until the end of the record was reached. Using unoptimized code the deconvolution for one data-set took 10 minutes on a 2GHz PC.

### **5.6.1 Results**

Figure 5.16 shows 100 traces from a marine VSP data-set. The overall data quality is good but there is quite a bit of noise preceding the first breaks, and the traces are quite ringy. Figure 5.17 is the result of applying source signature deconvolution following the method already outlined. A new filter is computed for every shot. Therefore any shot to shot variations are removed. The appearance of the data is very clean, with a lot of the ringing and noise having been removed.

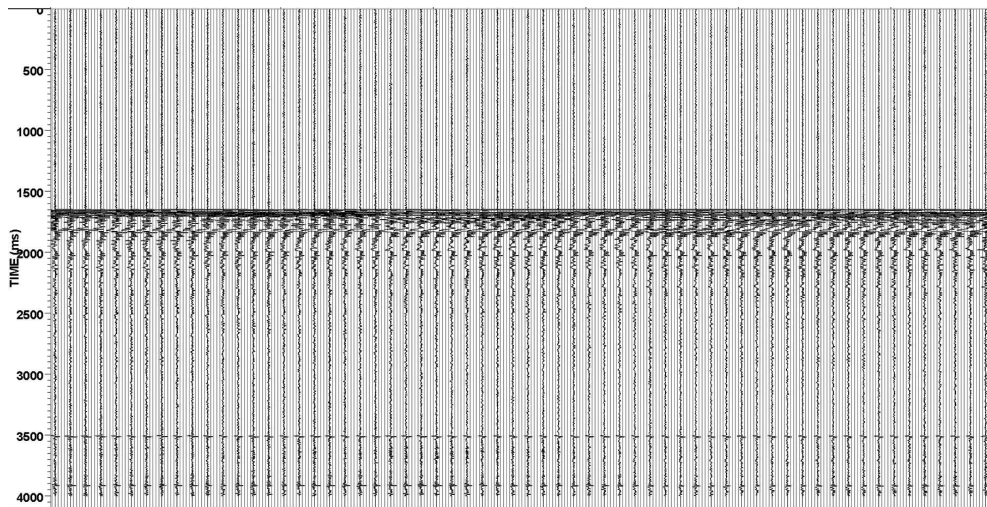


**Figure 5.16:** *Raw data from the Rosa VSP record.*

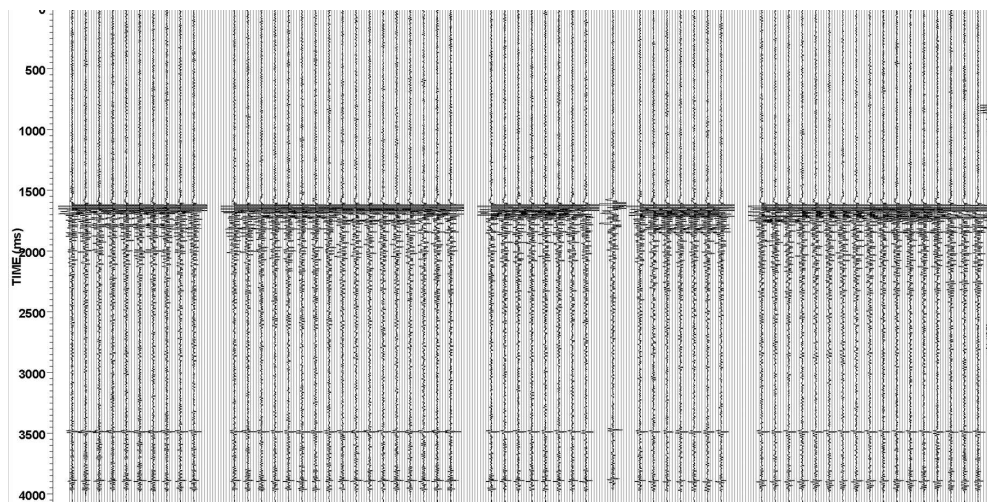


**Figure 5.17:** *The result of shot by shot source signature deconvolution.*

Even on this scale the consistency of the first arrival is obvious. In addition there seems to be some structure after the first breaks which is not visible on the raw data. Because the data are deconvolved to zero-phase the first break time is now maximum of the first arrival. This makes the data a lot easier to interpret, and the arrival at 3500 ms is now much clearer. Now that all the data have been deconvolved to the same wavelet the data can be stacked without the risk of introducing any artifacts. This is not a computationally intensive processing step and only involves slightly more complexity than the so called deterministic deconvolution currently being offered by service companies.

## **5.7 Conclusions**

The next step in the project would be to apply source signature deconvolution in a seismic while drilling environment, i.e while circulation and rotation is occurring. Unfortunately no suitable data are currently available to test the method in this setup. A seemingly obvious way to test the current algorithm in the presence of noise would simply be to add the noise. However, this would ignore the complex non-linear interactions which are certain to exist in a real SWD experiment. Currently the method has been shown to produce excellent results on noisy VSP data. However, it is envisaged, that some additional noise canceling would be required to pick the first breaks in a SWD environment where the noise can at least 25dB above the signal and is very broadband in nature. The canceling of this drilling noise was outside the scope of this work.

Application of the source signature deconvolution technique to VSP data and the data collected during the Uniwell experiment illustrate the robustness and power of the algorithm, and the suitability of it as the first step in any single imaging data processing strategy. It would have been ideal to have data from a field test of the magnetostrictive source to further test the algorithm. But at such date was not available. In order to overcome this limitation the new source was modeled in a single well imaging setup using 2D variable grid finite difference code and a simple cased borehole model.

The next chapter describes the modeling of three different downhole sources: a simple fluid-coupled explosive source, such as an airgun; the orbital vibrator source used in the Uniwell experiment; and the new magnetostrictive source. The aim is to highlight the differences between fluid-coupled and clamped configurations, to investigate the usefulness of downhole tube-wave attenuators, or baffles.

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# Chapter 6

## Finite difference modeling

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### 6.1 Introduction

In order to extract information about the structure and composition of the crust from seismic observations, it is necessary to be able to predict how seismic wavefields are affected by complex structures. Since exact analytical solutions to the wave equations do not exist for most subsurface configurations, the solutions can be obtained only by numerical methods. Various techniques for seismic wave modeling in realistic (complex) media have been developed. Explicit finite difference (FD) methods have been widely used to model seismic wave propagation in 2-D elastic media, because of their ability to accurately model seismic waves in arbitrary heterogeneous media. The FD software used to obtain the results presented here is based on the original work of Virieux [74] and Levander [45] who both formulated staggered-grid, finite-differences scheme based on a system of first-order coupled elastic equations where the variables are stresses and velocities. This distribution of wavefield and material parameters is referred to as the standard staggered grid (SSG). Robertsson et al. [63] extended the elastic SSG algorithms of Virieux [74] and Levander [45] to the viscoelastic case. To incorporate absorption they applied the "generalized standard linear solid" rheological model (GSLs) which was first proposed by Emmerich [21].

The main drawback of the FD method is that modeling of realistic scenarios consumes vast quantities of computational resources. Such computational requirements are generally beyond the resources for sequential platforms (single PC or workstation). In recent years it has become feasible to use clusters of workstations or PCs for scientific computing. FD modeling can benefit from this technique by using the open source implementation of MPI, the calculations are distributed on PCs or workstations which are connected by an in-house network. By clustering a set of processors, for example PCs running Linux, wall-clock times can be decreased and possible grid sizes can be increased significantly as demonstrated by Bohlen [8].

The spatial adaptation of the finite difference grid relative to the material parameters leads

to significant savings in computation time, and allows modeling of both small scale features and large scale structures such as boreholes and reservoir layers, respectively. One of the first attempts to implement a variable grid finite difference scheme was presented by Jastram and Belle [35]. They developed a method whereby the grid spacing is varied by a factor of three at the boundary between the coarse and fine grids. This can be repeated a number of times in order to vary the grid spacing from fine to coarse.

Recently Khn and Bohlen [40] have shown that this scheme becomes unstable as time progresses. These instabilities are due to non causal integration of fine grid points at the boundary between coarse and fine grid areas, by the symmetric FD operators. They modified the FD operators to be asymmetric, with the result that these points are integrated in a causal manner. Their new scheme is called asymmetric coarse to fine grid transition (ACFGT). The results presented here were generated using this ACFGT finite difference scheme. The code uses an open source implementation of MPI to run over a cluster of Linux PCs.

## 6.2 Theory

Synthesizing wave propagation in boreholes is made more difficult by the fluid solid boundary that must be included in the finite difference model. Most standard finite difference schemes are not stable for large differences in Poisson's ratio [71]. This problem can be overcome by using the staggered grid system developed by Virieux [74] as outlined below.

The seismic wavefield in a linearly elastic solid medium excited by a given source can be computed by stepping forward in time with the elastic wave equation. The most transparent and easily understood form of the elastic wave equation can be obtained from the equations relating strain and displacement, the stress strain relation (Hooke's law) and the law of conservation of momentum. Beginning with the relation between displacements and strain.

$$e_{ij} = \frac{1}{2} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) i, j = 1, 3 \quad (6.1)$$

The strains ( $e_{ij}$ ) are computed from the displacements ( $U_i$ ), using the stress strain relation for a general linear-elastic solid,

$$\sigma_{kl} = C_{ikl}e_{ik}i, k, l = 1, 3 \quad (6.2)$$

The stresses ( $\sigma_{kl}$ ) in the medium are then computed following the method outlined by Virieux [74]. The constants  $C_{ikl}$  describe the elastic properties of the medium. The quantities  $e_{ik}, U_i, \sigma_{kl}, C_{ikl}$ , are all functions of spatial position. Using the law of conservation of momentum, and substituting  $x, z$  for  $i, k$ , the particle accelerations can be calculated.

$$\frac{1}{\rho} \left[ \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z} \right] = \frac{\partial^2 U}{\partial t^2}, \quad (6.3)$$

$$\frac{1}{\rho} \left[ \frac{\partial \sigma_{zz}}{\partial z} + \frac{\partial \sigma_{xz}}{\partial x} \right] = \frac{\partial^2 U}{\partial t^2}, \quad (6.4)$$

$$\sigma_{xx} = (\lambda + 2\mu) \frac{\partial U}{\partial x} + \lambda \frac{\partial U}{\partial z}, \quad (6.5)$$

$$\sigma_{zz} = (\lambda + 2\mu) \frac{\partial U}{\partial z} + \lambda \frac{\partial U}{\partial x}, \quad (6.6)$$

$$\sigma_{xz} = \mu \left( \frac{\partial U}{\partial z} + \frac{\partial U}{\partial x} \right) \quad (6.7)$$

where  $U$  is the displacement vector and  $(\sigma_{xx}, \sigma_{zz}, \sigma_{xz})$  is the stress tensor,  $\rho(x, z)$  is the density,  $\lambda(x, z)$  and  $\mu(x, z)$  are lam coefficients. The system can be transformed into a first-order hyperbolic system as follows:

$$\frac{\partial v_x}{\partial t} = b \left( \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z} \right), \quad (6.8)$$

$$\frac{\partial v_z}{\partial t} = b \left( \frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z} \right), \quad (6.9)$$

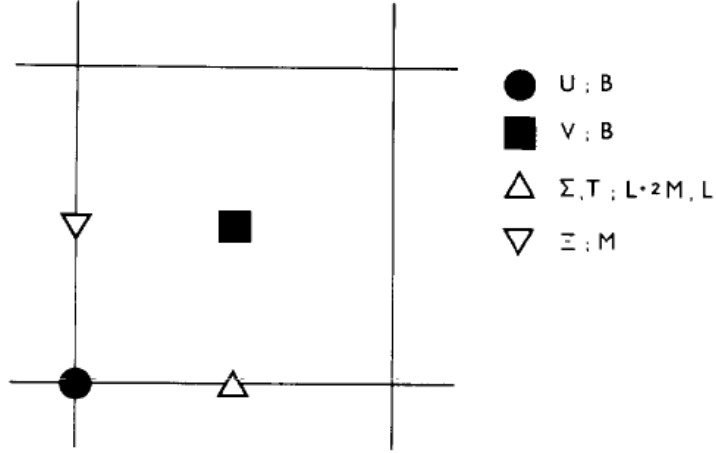


**Figure 6.1:** Discretisation of the medium on a staggered grid. The solid black symbols represent velocities and buoyancy at time  $k \Delta t$ , white symbols with a black outline represent stresses and Lam coefficients at time  $(k + \frac{1}{2}) \Delta t$ , from Virieux [74].

$$\frac{\partial \sigma_{xx}}{\partial t} = (\lambda + 2\mu) \frac{\partial v_x}{\partial x} + \lambda \frac{\partial v_z}{\partial z}, \quad (6.10)$$

$$\frac{\partial \sigma_{zz}}{\partial t} = (\lambda + 2\mu) \frac{\partial v_z}{\partial z} + \lambda \frac{\partial v_x}{\partial x}, \quad (6.11)$$

and

$$\frac{\partial \sigma_{xz}}{\partial t} = \mu \left( \frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x} \right), \quad (6.12)$$

where  $(v_x, v_z)$  is the velocity vector and  $b(x, z)$  is the buoyancy or lightness, which is the inverse of the density.

These derivatives are discretised using centred finite-differences. Assuming the equations are verified at the nodes, discretisation leads to a staggered grid setup as shown in Figure 6.1. The major difference between Virieux's scheme and the usual schemes was that the different components of the velocity field are not known at the same node. The explicit numerical scheme which is equivalent to the system outlined in equations 6.1 to 6.12 is as follows:

$$\begin{aligned}
U_{i,j}^{k+\frac{1}{2}} &= U_{i,j}^{k-\frac{1}{2}} + B_{i,j} \frac{\Delta t}{\Delta x} \left( \Sigma_{i+\frac{1}{2},j}^k - \Sigma_{i-\frac{1}{2},j}^k \right) \\
&+ B_{i,j} \frac{\Delta t}{\Delta z} \left( \Xi_{i,j+\frac{1}{2}}^k - \Xi_{i,j-\frac{1}{2}}^k \right), \tag{6.13}
\end{aligned}$$

$$\begin{aligned}
V_{i+\frac{1}{2},j+\frac{1}{2}}^{k+\frac{1}{2}} &= V_{i+\frac{1}{2},j+\frac{1}{2}}^{k-\frac{1}{2}} + B_{i+\frac{1}{2},j+\frac{1}{2}} \frac{\Delta t}{\Delta x} \left( \Xi_{i+1,j+\frac{1}{2}}^k - \Xi_{i,j+\frac{1}{2}}^k \right) \\
&+ B_{i+\frac{1}{2},j+\frac{1}{2}} \frac{\Delta t}{\Delta z} \left( T_{i+\frac{1}{2},j+1}^k - T_{i+\frac{1}{2},j}^k \right), \tag{6.14}
\end{aligned}$$

$$\begin{aligned}
\Sigma_{i+\frac{1}{2},j}^{k+1} &= \Sigma_{i+\frac{1}{2},j}^k + (L + 2M)_{i+\frac{1}{2},j} \frac{\Delta t}{\Delta x} \left( U_{i+1,j}^{k+\frac{1}{2}} - U_{i,j}^{k+\frac{1}{2}} \right) \\
&+ L_{i+\frac{1}{2},j} \frac{\Delta t}{\Delta z} \left( V_{i,j+1}^{k+\frac{1}{2}} - V_{i,j}^{k+\frac{1}{2}} \right), \tag{6.15}
\end{aligned}$$

$$\begin{aligned}
T_{i+\frac{1}{2},j}^{k+1} &= T_{i+\frac{1}{2},j}^k + (L + 2M)_{i+\frac{1}{2},j} \frac{\Delta t}{\Delta z} \left( V_{i,j+1}^{k+\frac{1}{2}} - V_{i,j}^{k+\frac{1}{2}} \right) \\
&+ L_{i+\frac{1}{2},j} \frac{\Delta t}{\Delta x} \left( U_{i+1,j}^{k+\frac{1}{2}} - U_{i,j}^{k+\frac{1}{2}} \right), \tag{6.16}
\end{aligned}$$

and

$$\begin{aligned}
\Xi_{i,j+\frac{1}{2}}^{k+1} &= \Xi_{i,j+\frac{1}{2}}^k + M_{i,j+\frac{1}{2}} \frac{\Delta t}{\Delta z} \left( U_{i,j+1}^{k+\frac{1}{2}} - U_{i,j}^{k+\frac{1}{2}} \right) \\
&+ M_{i,j+\frac{1}{2}} \frac{\Delta t}{\Delta x} \left( V_{i+1,j}^{k+\frac{1}{2}} - V_{i,j}^{k+\frac{1}{2}} \right) \tag{6.17}
\end{aligned}$$

where  $k$  is the index for time discretisation,  $i$  for  $x$ -axis discretisation and  $j$  for  $z$ -axis discretisation.  $\Delta t$  is the time-step:  $\Delta x$  and  $\Delta z$  are the spatial grid steps for the  $x$ -axis and

$z$ -axis, respectively, for simplicity these are assumed to be equal in following relationships. Velocity  $(U, V) = (v_x, v_z)$  at time  $(k + \frac{1}{2}) \Delta t$ , and stress  $(\Sigma, \Xi, T) = (\sigma_{xx}, \sigma_{zz}, \sigma_{xz})$  at time  $(k + 1) \Delta t$  are computed explicitly from velocity at time  $(k - \frac{1}{2}) \Delta t$  and stress at time  $k \Delta t$ .  $B$  is the buoyancy within the medium and  $L$  and  $M$  are the Lam coefficients  $(\lambda, \mu)$  as shown in Figure 6.1.

The geometry of the model and the finite computing power restraints require the introduction of artificial boundaries to the model. The formulation and type of boundary is very important. Poorly chosen boundary conditions can introduce artifacts into the data that may be confused with physical reflections or refractions. Absorbing boundary conditions based on those formulated by Reynolds [64] are used. This is an ideal choice on a staggered grid as only values on lines normal to the absorbing surface are used.

### 6.3 Motivation

The overall aim of the work presented in this chapter was to investigate the behaviour of different types of downhole sources in a SWI set up. One aspect was to assess the difference in the ratio of tube-wave to body-wave energy between clamped and fluid-coupled sources. Another aspect was to investigate the effect of cement-bonded steel casing and simple low-velocity tube-wave dampers in the hole.

### 6.4 Method

Two model geometries were investigated. The first contained a multiply-cased borehole in a homogeneous formation. The second model contained the same formation parameters as the first, but the source was moved to the centre of the hole and tube wave suppressors we added. Ideal clamped and fluid-coupled sources were simulated in both models, using a Ricker wavelet as the input. In addition, the OVS and magnetostrictive sources were also simulated by using their respective source signatures as the input. The following sections give a description of the models and a brief overview of the code and the input parameters used to run the simulations.

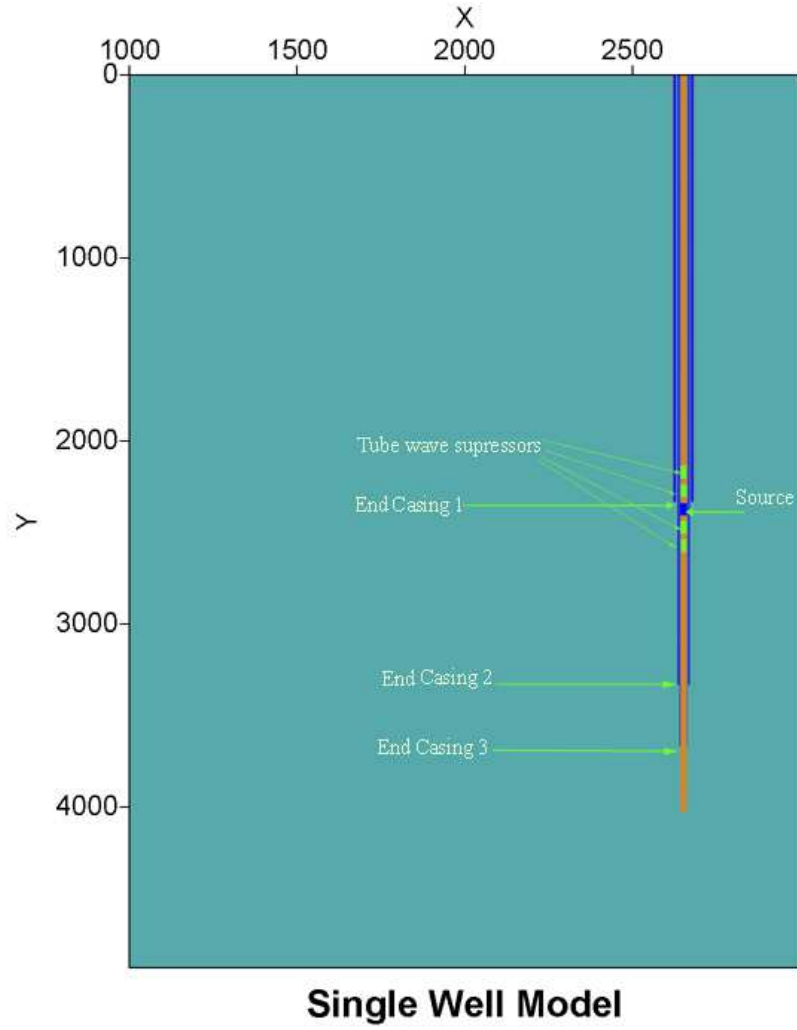


**Figure 6.2:** Cased Borehole model used for FD simulations with and without suppressors. Units are grid points in the  $x$  and  $y$  direction where the  $y$  axis is depth.

#### 6.4.1 Model Description

The initial model as shown in Figure 6.2 had the dimensions  $65 \times 71 \text{ m}^2$  and contained one multiply cased borehole with a radius of 15 cm. The borehole contained a seismic source, at a depth of 30m, was filled with water ( $V_p = 1500 \text{ ms}^{-1}$ ,  $V_s = 1 \times 10^{-6} \text{ ms}^{-1}$ ,  $\rho = 1000 \text{ kgm}^{-3}$ ), and contained 140 receivers, between 3.6 m and 69.6 m depth. The surrounding formation was a crystalline host rock with  $V_p = 3000 \text{ ms}^{-1}$ ,  $V_s = 1930 \text{ ms}^{-1}$ ,  $\rho = 1600 \text{ kgm}^{-3}$ .

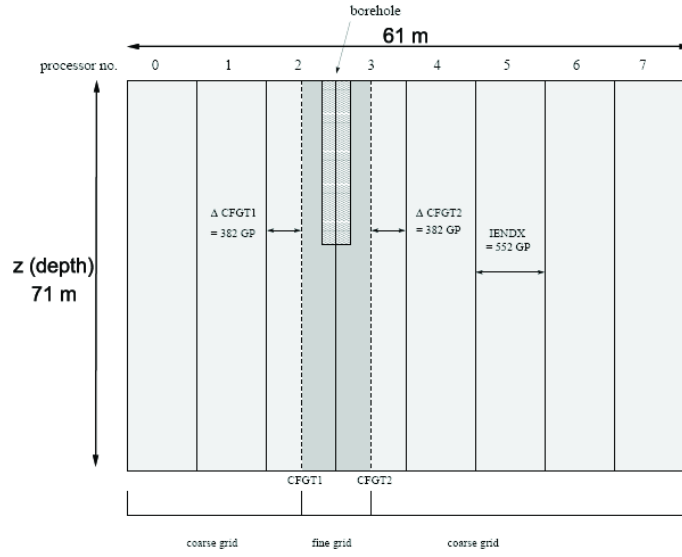


**Figure 6.3:** Grid decomposition for variable grid 2D finite difference simulations.

The source signal used to simulate the ideal explosive and clamped source was a Ricker wavelet, with a central frequency of 200 Hz. The recorded source signatures from the OVS and magnetostrictive sources were used to simulate the realistic fluid-coupled and clamped sources respectively. To avoid numerical grid dispersion of body waves, a grid spacing of 17 cm was used. However, the tube waves and the borehole structure require a denser sampling of 1.5 cm. The corresponding time step interval is  $dt = 1.85 \times 10^{-6} s$ . The spatially variable grid reduces the computational costs by dividing the model into coarse and fine areas. In the finely sampled areas surrounding the borehole, a grid-point distance  $dh_1 = .015m$  is used. The coarsely sampled area outside the boreholes is discretised with  $dh_1 = .03m$ . The transition between the coarse and the fine grid (denoted as CFGT) on the left of the borehole (cftg1) is located at 22.28m and the transition between the fine and coarse grid on the right of the borehole (cftg2) is located at 27.32 m. The positions of the CFGTs are indicated in Figure 6.3 as vertical dashed lines.

Figure 6.3 shows the decomposition of the model geometry for the initial model. To make sure that the different computational domains are coupled correctly, so that the seismic waves can travel from one domain to another, the number of grid points in a domain  $IENDX = NX/NPROC$  must be an integer multiply of 2. For these examples  $NX = 4416$ ,  $NPROCX = 8$  and get  $IENDX = 552$ ,  $IENDX/2 = 276$ . To get the

maximum reduction of computational time the fine grid (borehole) is placed symmetric to a domain-boundary in  $x$ -direction, so that the fine grid can be calculated by 2 processors. To couple the CFGTs with the domain boundaries, the distance between CFGT1 and the left domain boundary (CFGT1) and the distance between CFGT2 and the right domain boundary (CFGT2) must also be an integer multiple of 2.

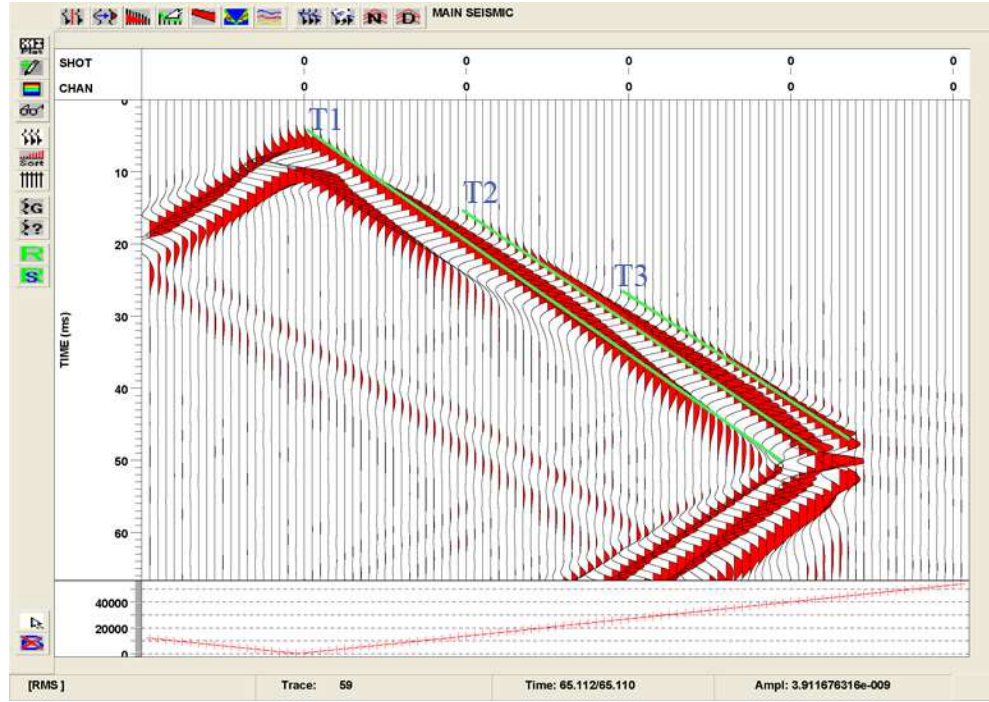


**Figure 6.4:** *Ideal explosive source hanging free in the fluid with clamped geophones.*

## 6.5 Results and Discussion

### 6.5.1 2D simulation of ideal downhole sources homogenous model, cased borehole

Figure 6.4 is the result of modeling an explosive source hanging free in the fluid, in a multiply-cased borehole. The data is displayed with the receiver locations on the  $x$ -axis increasing in depth from left to right, and with time on the  $y$ -axis. The only notable events are the tube waves. T1 is the tube wave direct from the source, T2 is a new tube wave formed as T1 passes the first casing shoe, T3 is the tube wave created when T2 passes the second casing shoe. All of these events are reflected from the bottom of the hole. In addition T1 is also

reflected with reduced amplitude (due to damping) from the top of the model. The main result here is that no clear body wave arrivals are present. This is very similar to the data collected during the Uniwell experiment.

Figure 6.5 is the result of modeling an ideal clamped source within a cased borehole and using clamped receivers. The main event of Figure 6.4 is still visible but there is also a strong P-wave arrival visible, denoted by P1. This is also visible as a reflection from the top and bottom of the model, denoted by P2. Other more complex interactions are visible which may be due to casing waves and additional trapped modes propagating in the concrete bonding between the casings.

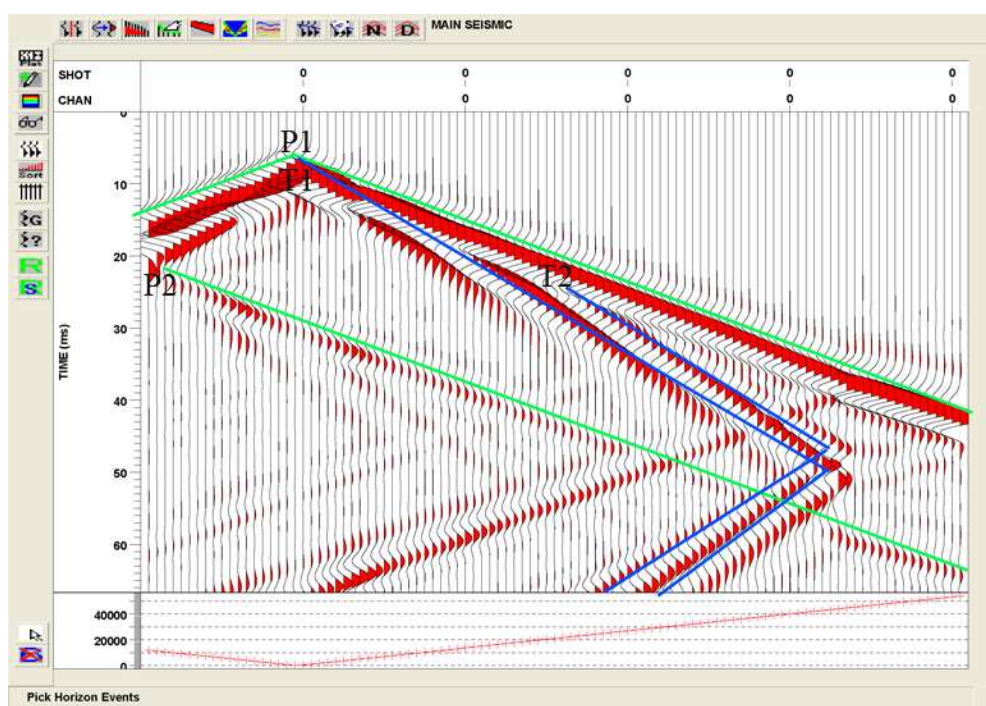


**Figure 6.5:** *Ideal clamped source with clamped receivers.*

### 6.5.2 2D simulation of the orbital vibrator and magnetostrictive source.

Using an ideal wavelet in the simulations results in the best possible resolution and hence the easiest interpretation. This approach has clearly highlighted the advantage of clamped sources over a fluid-coupled source. However, in order to compare the orbital vibrator source and the magnetostrictive source in a realistic situation it is necessary to replace the ideal wavelet with a recorded source signature. This makes it possible not only to see the advantages of clamping, but also to investigate the PRBS driving method and compare the results with the processed

OVS data.

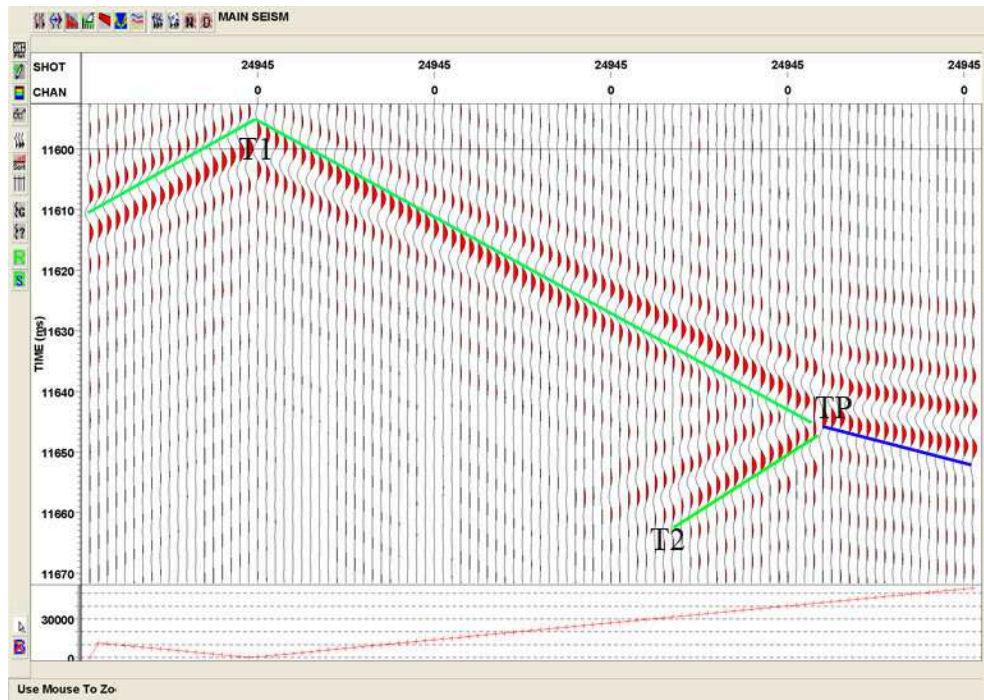


**Figure 6.6:** *Orbital Vibrator Source clamped receivers.*

Figure 6.6 is the result of modeling the OVS source. All receiver positions and model parameters are identical to that used in Figure 6.4. The data were processed using cross correlation with the recorded source signature. The resolution difference between the ideal wavelet and the wavelet produced by correlation is clear. Most of the events visible in Figure 6.4 are obscured by the ringy character of the OVS wavelet with only the high amplitude primary tube wave visible. It is clear that the ringy character of the OVS wavelet further compounds the problems caused the fluid-coupled source. Source signature deconvolution would improve this result, as seen in the Uniwell results. However, cross-correlation is the normal processing method for the OVS source and as such represents a more accurate comparison.

Figure 6.7 represents the result of modeling the magnetostrictive source in the same cased borehole model. The input to the model was a 5 s long PRBS signal, recorded during the tests of the magnetostrictive source in the granite block. The raw data were then cross-correlated with the input PRBS to produce the record shown in Figure 6.7.

As in the case with the ideal clamped source there are clear body wave events visible denoted by P1 and P2. In addition, there are also tube wave events denoted by T1, T2, and T3. The

result is not as clear as Figure 6.5 due in part to the more complex side-lobes of the PRBS wavelet which has obscured certain more subtle events. However, there is a strong similarity with the result shown in Figure 6.5. It is clear that driving the source with a coded waveform results in a much more ideal type wavelet and excellent resolution. The fact that the PRBS used for this simulation had a duration of only 5s reinforces the point made in the magnetostrictive source discussion, that if the source is well coupled to the formation run times can be reduced from the experimental time of 80s to a much shorter more practical time.

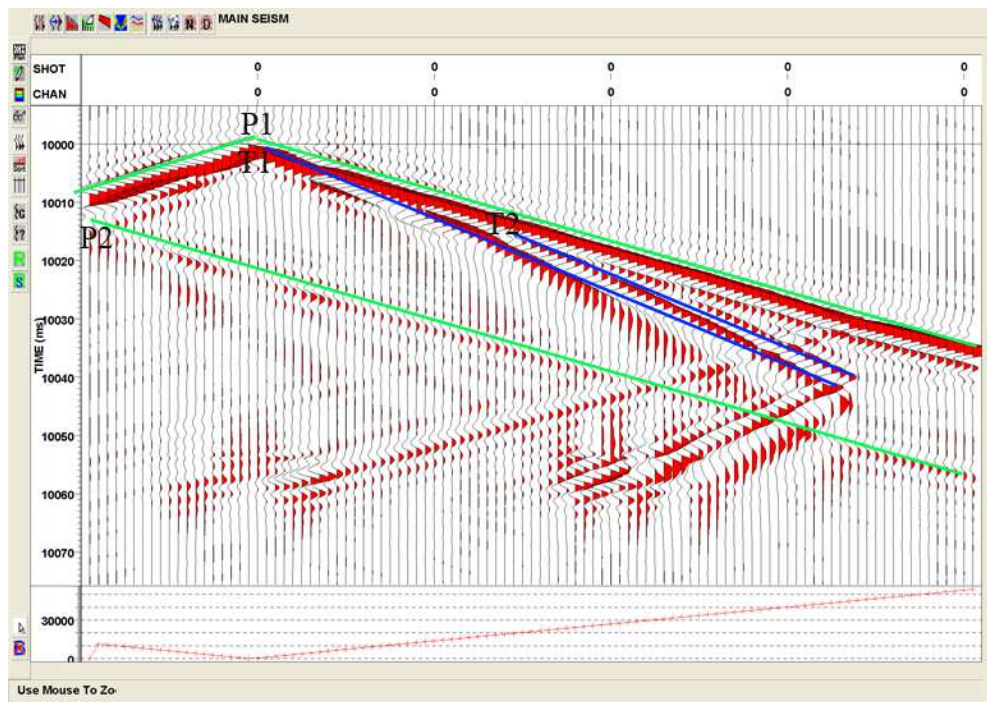


**Figure 6.7:** *Clamped Magnetostrictive source, clamped receivers.*

### 6.5.3 Tube wave suppression results

Figure 6.4 highlights the problems inherent with fluid-coupled sources, namely the large transfer of energy to the fluid column in the form of tube waves. Despite this obvious drawback, fluid-coupled sources are still regarded by some to be the preferred choice for single well imaging. This is largely due to the belief that the tube wave problem can be solved or at least mitigated by the use of tube wave suppressors in the borehole. Many different designs have been proposed for these tube wave suppressors, some simple and some esoteric. The simplest form is a low density low velocity cylindrical packer which is thought to absorb some of the

tube wave energy as it passes through along the fluid column. This design has been used to produce the results described in this section.

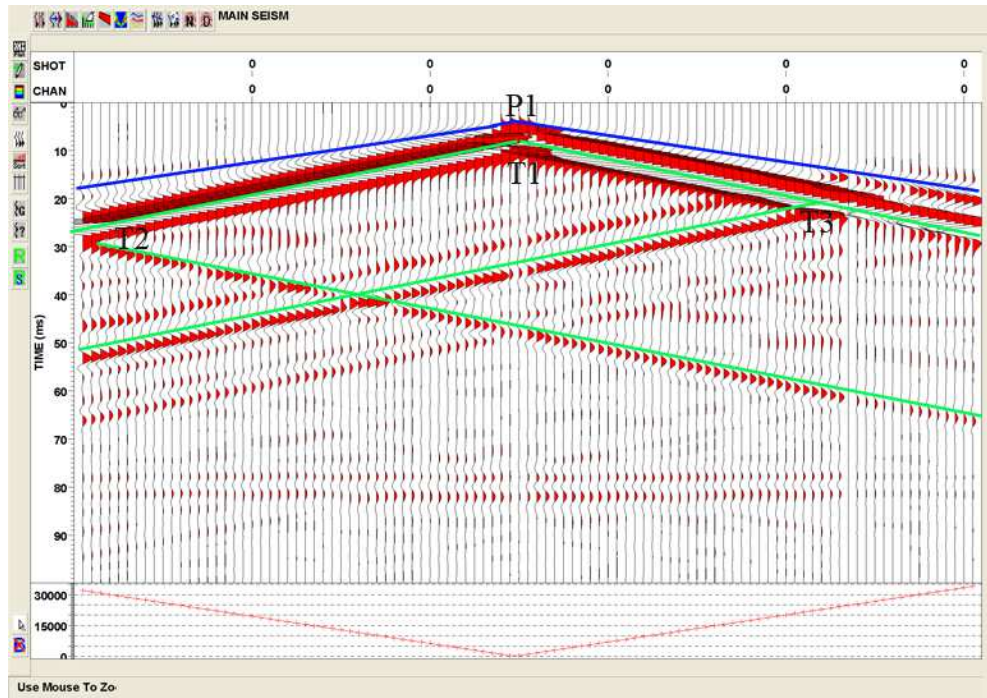


**Figure 6.8:** *Ricker wavelet source with no tube wave suppression.*

Figure 6.2 illustrates the model setup used in this section the source is more centrally placed than in the previous simulations in order to assess the performance of the tube wave suppressors either side of the source.

Figure 6.8 is the result of modeling an ideal fluid-coupled Ricker wavelet source in the model of Figure 6.2. Strong tube wave events denoted by T1, T2 and T3 are visible there is also a very low amplitude event which could be a P-wave extrapolated back as P1.

Figure 6.9 shows the same setup but this time with the addition of tube wave suppression devices either side of the source. The very low velocity of the suppressors has caused some small scale dispersion on the traces in the immediate vicinity. However, this does not seem to have affected the other traces. It is clear that the devices have reduced the tube wave amplitude. However, the P-wave event denoted by P1 is still at a much lower amplitude.

Whilst the tube wave suppression devices have been shown to be partially effective in this idealistic case, given the performance of the OVS source in Figure 6.6 they are unlikely to

suppress the tube sufficiently to uncover the body waves.

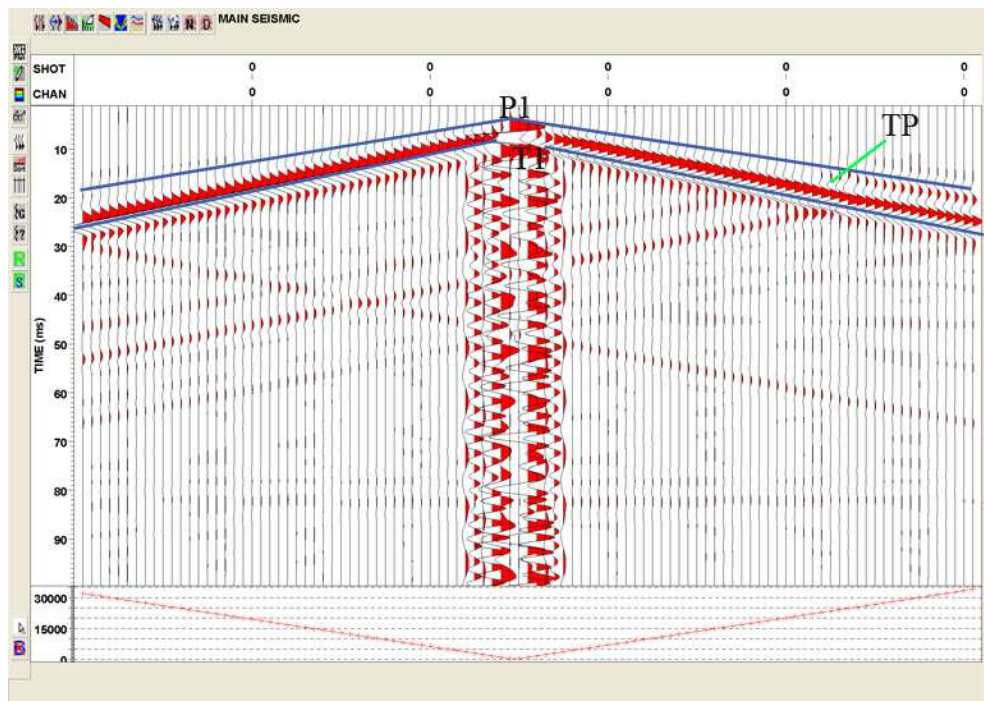


**Figure 6.9:** *Ricker wavelet source with tube wave suppression.*

## 6.6 Conclusions

The aim of the research described in this chapter was, firstly, to investigate whether the assumption implicit in the design of the magnetostrictive source, that a clamped source should produce less tube waves was correct, and, secondly to investigate the advantages of the PRBS driving method over the swept signal used by the OVS source. The third final aim was to investigate whether tube wave suppression devices were a viable solution to the tube wave problem inherent with the OVS source.

The results clearly show that in comparison to the an ideal fluid-coupled source the clamped source transfers much less tube wave energy to the formation. This is illustrated by fact that no body wave arrivals are visible in Figure 6.4 whereas there are clear P-wave events in Figure 6.5, which represents the clamped source. To date fluid-coupled sources have been preferred to clamped sources mainly from a mechanical risk point of view. A fluid-coupled source by its very nature is unlikely to get stuck in the hole and it is also much faster to deploy and move

between shots. However, both the modeling results here and the actual Uniwell data show that the tube wave noise issue is a high price to pay.

The results of the real wavelet simulations further reinforce the clamped source argument whilst at the same time highlighting the strength of the coded waveform driving technique. In this case the OVS result when processed using cross correlation with the sweep gives a very poor ringy record with only the primary tube wave visible. In contrast to this the coded waveform technique when processed in exactly the same way yields an excellent result which closely matches that of the ideal wavelet source.

This highlights both the advantage of the coded waveform and the simplicity of the processing step. Source signature deconvolution would vastly improve the result of the OVS simulation. However, it would be impossible to improve on the ideal simulation. The coded waveform data can be processed using either method and still give excellent results, whereas the OVS data must be processed using source signature deconvolution and even then this optimal processing method can only hope to improve the resolution of the tube events.

To conclude the results from both the ideal wavelet simulations and the recorded wavelet simulations clearly show that a clamped source, driven using a coded waveform, in a single well imaging setup, can transfer enough energy to the formation, so that body waves are made visible. This is currently not demonstrably possible with state of the art downhole sources. Whilst a clamped source can slow down surveying and carries some risk, this research proves that it is a viable option for single well imaging.

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## Chapter 7

# Conclusions and Limitations

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The purpose of this chapter is to restate the aims of the research and to investigate how well these aims were met and to explain any limitations. In addition the chapter summarizes the work presented in the previous chapters, highlights and discusses the conclusions drawn from the novel findings in each chapter, and finally makes suggestions as to the direction of further research.

The overall aim of this research was to develop and improve on the single well imaging concept pioneered in the Uniwell project. The work focused on three main areas of research: reprocessing of the Uniwell data which led to the development of a new data processing system for VSP and SWD surveys; design and testing of a new downhole source that could overcome the problems associated with the OVS source; and finally, finite difference modeling of the SWI setup using the OVS source and the new magnetostrictive source. The main reason for the modeling step was to illustrate the effectiveness of a clamped source driven using a coded waveform as compared to a fluid-coupled source. Ideally this would have been done using real data from a field survey, but this was not possible in the given timescale. What follows is a brief recapitulation of the most important results and conclusions from these three strands of research.

The Uniwell experiment was the first attempt to develop the concept of single well imaging, and as such it was well supported by both industry and the DTI. Unfortunately, as is often the case with pioneering work and novel research in general, major obstacles were encountered which slowed the progress of the project and finally brought it to a premature end. Fortunately the data that were gathered were of excellent quality and this formed the basis and indeed the initial motivation for the work discussed in this thesis. Perhaps the biggest problem with the Uniwell experiment was the high amplitude tube-wave events which traveled up and down the borehole obscuring any other arrivals. Source signature deconvolution of the OVS data did succeed in compressing the tube-wave events and a secondary deconvolution, this time using the reflected tube-wave as a signature, uncovered body wave arrivals on two out of four receivers.

Unfortunately, due to the low number of receivers it is impossible to verify the consistency of these arrivals.

EMD was employed to try and improve on these results, and some significant wave modes were extracted with arrivals which had a P-wave move out velocity. However, the tube-wave noise was still present and made the determination of other arrivals rather ambiguous in nature.

The limitations in the Uniwell work centred around the fact that the received signals could not be separated into linear equivalents, due to the source only being spun in one direction. In addition the low number of receivers led to difficulty in positively identifying arrivals on the reprocessed data. Perhaps the most important findings of the Uniwell work were that fluid-coupled sources were very poorly suited to SWI and that while it was possible to compress the tube-wave and improve the overall resolution using source signature deconvolution and EMD, in order to develop a robust single well imaging strategy a new source design was needed which did not transfer so much energy to the fluid.

Clamped downhole sources had been proposed before, and indeed they were built and extensively tested, but very little published data exists for these tests. Perhaps the most well known was the Sandia source which was developed and tested around 1997. This was aimed at environmental surveys conducted in shallow boreholes, but the application to single well imaging did not go unnoticed and it is possible that service companies initiated research programs to develop a downhole source based on the Sandia design. Very little ever came of this research, probably due to major design problems with the Sandia source.

The basis of the source was a magnetostrictive actuator which drove against a heavy reaction mass. The source was mechanically clamped to the borehole wall and the vertical motion of the source moving against the reaction mass transferred shear wave energy to the formation. The major flaw in this design was that the large reaction mass would frequently hit resonance points, imparting large shear stresses to the magnetostrictive material which, whilst very strong under compression, was brittle under shear. This led to a much higher risk of shattering the material. Understandably these fundamental problems lead to magnetostrictive sources becoming less and less attractive. Eventually research all but ceased, coinciding with the decline in single well imaging research and the drop in oil prices in the late 1990s and early 2000.

The work described here solves the problem of back EMF and resonance by driving the actuator using a coded waveform which avoids excitation of the resonant frequencies. The results

are then cross correlated with the pilot PRBS and the effect of the time bandwidth product is utilised to extract the signal from the noise. In addition coded waveforms, with very low side lobe energy can be used to improve the resolution of the data. The power of the method is illustrated in the granite block experiment. The results show the signal rising up out of the noise as the length of the coded waveform is increased, i.e as the “time” variable of the time bandwidth product is increased.

The limitations of the design resulted in very long run lengths being required to pull the signal out of the noise. This was directly related to the poor energy transfer between the source and the formation due to the overall stiffness of the system and the small surface area contacting the borehole wall. Limitations aside, the results here proved that the resonance problems with the magnetostrictive source could be solved by using a coded wave form driving method. Furthermore, the processing gain possible with the coded waveform was shown to be excellent. The most obvious next step in the research would have been a small scale field test.

This was to be the subject of another project, planned as a collaboration between the University of Edinburgh and Baker Hughes Inteq. Despite positive early discussions the project did not go ahead, mainly due to budgetary constraints. However, it was decided to go ahead with the first stage of the project independently, which was to further test the source design using finite difference modeling.

Before the modeling stage additional work was put into developing the data processing strategy from the Uniwell work, as it was clear that the source signature deconvolution step also had possible applications in both conventional VSP surveying and in the SWD techniques currently being developed. To this end a system was developed whereby data could be collected downhole during pauses in drilling, in a VSP type setup. These data could then be source signature deconvolved downhole using either the recorded source signature or a signature taken from a library file.

After deconvolution, the first break would move from the first departure from zero to the maximum value within a given window. This value would then be sent up-hole and thus the position of the drill-bit could be determined. The whole process can be executed very quickly during pauses in drilling.

The principle of the system was tested using both noisy and good VSP data. The results were excellent, showing very good performance in all situations. This is illustrated by deconvolution

of an entire VSP record on a shot-by-shot basis: all source signature variations were removed along with a lot of additional noise. It had been intended to extend the technique to operate whilst circulation and drilling was taking place. However, initial research suggested that the noise was very broadband in nature and exhibited very little structure. Removal of this noise was impossible given the limitations of the data available.

The work concludes with an investigation of the performance of both ideal and realistic downhole sources in a single well imaging setup. In addition a simple tube-wave suppression device was investigated. The scope of the finite difference research underwent more changes than any other aspect of this thesis, mainly due to computational and time limitations. Initially a full 3D investigation using a realistic sub-surface velocity model was planned. However, problems with adapting existing code to run in a parallel environment and the limitations of a loosely clustered collection of Linux PCs made this very difficult. An attempt was made to run the 3D code on the massive parallel machines in EPCC. However, the relative slowness of the CPUs resulted in very little speedup compared to the Linux cluster. As a result, the aims of the modeling were redefined to use a simple 2D model to compare the sources. In hindsight it was perhaps unnecessary to use a complex model as the characteristics of interest were relatively simple and perhaps more clearly observable in a model of low complexity.

The results from the ideal source modeling backed up the decision to move to a more simple model. The difference in tube-wave generation between the fluid-coupled and clamped source is very clear, with little or no body wave energy visible for the fluid-coupled source simulation and a clear P-wave on the clamped source simulation. This result validated the initial assumptions behind the magnetostrictive source design, i.e. that a clamped source would produce less tube-wave energy. However, another aim of the work was to compare the OVS source to the magnetostrictive source. In order to do this, the ideal Ricker wavelet was replaced by the relevant recorded source signatures. The data were then processed in the conventional manner using cross correlation with the signature.

The results are striking. Whilst the magnetostrictive source simulation compares very well to the ideal clamped source data, the OVS simulation has a very ringy character and only the primary tube-wave event is clear. This result proves that not only is a clamped source much more effective in a SWI setup but also that the coded waveform driving method gives a near ideal processed wavelet, whereas the OVS method results in a very ringy wavelet with multiple side-lobes.

One solution to the tube-wave problem, put forward by advocated of the OVS source, is to use dampers in the borehole to suppress the tube wave. This is still an area of active research. It was decided, therefore, to test a very simple type of damper, namely a low density, low velocity material, spaced above and below the source in the hole. The results show that whilst some tube-wave attenuation is accomplished, the tube-wave is still dominant over the body waves. The effect of adding the dampers is insignificant compared to the result of using a clamped source driven using a coded waveform.

The results in the final chapter complete the work. At the outset of the research the intention was to develop the building blocks of a successful single well imaging system, to test them and illustrate how they could work together in a real setup. Each step builds on the next as the source design grew out of the Uniwell data processing and this was then extended to both a the more general VSP setup and a state of the art SWD application. Despite computational limitations, the finite difference results illustrate the reason for using a clamped source and also highlight the benefits of the coded waveform driving method.

Perhaps the most interesting and important conclusion to take from this work is that the seemingly intractable problems surrounding the single well imaging method can all be solved by a thorough and logical redesign of the entire system from the mechanical source through to the final data processing.

It is hoped that the results outlined in this work can serve as a road map for further research leading to a commercially viable single well imaging system. The next stage of this would be to further investigate EMD as a method for tube-wave removal, to rebuild the source in order to improve the hydraulic amplification potential, and also to investigate the possibility of using other actuators rather than the fragile magnetostrictive type. The final step would be to repeat the finite difference simulations in a real field test where the source would be compared to other state of the art sources. The Humble test site would be a perfect location given the availability of the Uniwell data. In addition it would be nice if the work was completed in the same place where the first steps were taken.

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# Appendix A

## Publications

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- B. Walsh, A. Ziolkowski, S. McLaughlin, J. Dripps, and A.Brand, “Design and testing of a new magnetostrictive borehole source for single well imaging and seismic while drilling applications SEG Expanded Abstracts 24, 2653 (2005)
- B. Walsh, A. Ziolkowski, S. McLaughlin, Edinburgh University, Holger Mathiszik and Graham Gaston, Baker Hughes Inteq, Celle “Source signature deconvolution for VSP applications, submitted for 2007 SEG Annual meeting, San Antonio.

## Design and testing of a new magnetostrictive borehole source for single well imaging and seismic while drilling applications:

*Brendan Walsh\*, Anton Ziolkowski, Steve McLaughlin, Jimmy Dripps and Alistair Brand, The University of Edinburgh*

### Summary

We have developed a new hydraulically clamped downhole magnetostrictive source, driven using a coded continuous waveform method, which does not suffer from the problems which have been associated with magnetostrictive sources in the past, such as resonance and generation of large back emf. The hydraulic clamping arrangement leads to the majority of the source energy being transmitted to the formation, with minimal tube wave generation. We have tested a prototype source in a cored 5000 kg granite block with four accelerometers mounted on the outside of the block. We have successfully identified arrivals at all accelerometers. The source was initially developed for wireline single well imaging but due to its light weight, slim dimensions, and low power consumption it could also be incorporated into the drill string and utilized in look ahead of the bit applications while drilling.

### Introduction

One current state-of-the-art borehole source is the Orbital Vibrator Source (Cole, 1997); this is a fluid-coupled source which generates circularly polarized waves by rotating an eccentric mass inside a steel casing. It is essentially a volume displacement source that results in the generation of large amplitude tube waves. Dale and Cox (1999) showed that in order to decompose the circularly polarized data the source has to be swept in clock-wise and counter clock-wise directions, meaning two shots are needed for every level; this, along with the need to clamp and unclamp the cable for every level, leads to increased survey times compared with an airgun source.

There is a clear need and demand in the industry for a downhole source which produces minimal tube waves and is robust and portable enough for a variety of borehole applications. A clamped source built around a magnetostrictive actuator is a good choice: clamping the source couples the energy directly into the formation and not the fluid, minimizing tube wave noise. The magnetostrictive actuator is mechanically very efficient and has been tested at depths of 1000m and 100 deg c.

Cutler et al. (1997), describe Sandia's attempt to design and build a downhole magnetostrictive actuator. Their initial design utilized an off-the-shelf actuator from Etrema mounted so as to drive a large reaction mass. The source was electrically clamped and driven using a chirp signal.

One major problem they encountered were resonances at 250Hz and harmonics; another problem was the large back emf encountered if the actuator was suddenly switched off.

Our first step in the source development was to recreate one of Sandia's experiments; the actuator and large 5kg tungsten reaction mass were mounted on a granite block and driven with a chirp signal. We encountered the same problems of resonances and the back emf. This resulted in the partial destruction of one actuator. It was clear a new approach was needed (UK Pat App 0424808.4).

The solution was to remove the reaction mass, redesign the tool, and drive the actuator using a long coded continuous waveform signal. This enabled us to avoid all resonances, permitting us to drive the tool at higher power. The tool has a master hydraulic reservoir filled with an essentially incompressible fluid under pressure; the pressure is modulated by the motion of the actuator push rod. Two slave cylinders are connected to the master reservoir and apply pressure at the borehole wall. In our initial set up just one set of clamps transmits the signal to the formation; the top clamps simply fix the tool in place. In the next section we describe some of the theory behind the coded waveform approach and the data processing method. We then present results from testing in a cored granite block, showing clear arrivals at receivers mounted on the block.

### Theory and methodology

Winbow (1991) showed analytically that a clamped point source emits most of its energy into the formation, while a fluid-coupled acoustic source such as an airgun or an orbital vibrator emits most of its energy as tube waves. Our source is clamped at four points on the borehole wall; this ensures a good contact with the borehole wall and prevents any sort of rocking which can happen if there is just one clamping point. If the surface area of the clamping shoe is greater than the area of the actuator rod, the force output by the clamping shoe will be proportionately higher than the force input by the actuator. Therefore we can amplify the force input by making the clamping area larger.

Hall et al. (1995) showed experimentally that when a similar actuator was driven at high amplitudes its impulse response became non linear and large resonances were present, which could damage the material. They relate this to the shape of the hysteresis loop of the material. Therefore the resonances are a characteristic of the

### Magnetostrictive borehole source

magnetostrictive material and not the framework the actuator is built into. These resonances are similar to what we experienced in our initial testing with the reaction mass. We avoid this problem by using the coded waveform method. Because of this the source is never spends enough time at any frequency to excite resonances.

We choose a short coded pseudo random binary sequence of 1023 bits as the driving input to the actuator. This can be thought of as a series of pulses. The code was designed to have good autocorrelation properties, especially low side lobe energy. Multiple copies of this single sequence were sent out in a continuous sequence for a given run length. The received signal was processed by cross correlation with the reference signal. This is a matched filter, and has the effect of pulling the signal up out of the noise. The processing gain is related to the time bandwidth product. The longer the coded sequence the larger is the gain. The length of the sequence, i.e. the run time for the source, should be chosen to provide enough processing gain to lift the signal out of the noise, whilst keeping the record lengths to a reasonable size.

Coded continuous sequences have a major advantage over pulses, namely, their time-bandwidth product. The term "time-bandwidth product" (TB) comes from the relation between a pulse's duration in time and the frequencies necessary to construct them (its bandwidth). This is simply

$$t_b = \tau \delta \nu \quad (1)$$

where  $\delta \nu$  is the bandwidth and  $\tau$  is the observation time. Therefore a 1ms pulse will have a bandwidth of 1 KHz and a time bandwidth product of 1. However, in a unique, i.e. non-repeating, coded continuous waveform with 1000 binary digits and duration of one second, each binary digit is in itself a pulse with duration of 1 ms and a bandwidth of 1 kHz. So the bandwidth of the overall sequence is of the order of 1 kHz, but the observation time is 1 sec compared to 1ms for the pulse and so the TB product for the coded waveform is 1000.

The processing gain at the receivers when a matched filter is employed, i.e. when we correlate the received signal with the reference signal, is  $10 \cdot \log_{10}(TB)$  better than the signal-to-noise ratio before or after a signal is detected. For a TB of 1000 this is 30dB, so a signal which is 20dB below additive and uncorrelated noise will be 10dB above after filtering using this method, making it clearly detectable.

In our initial design the ratio of the size of the clamping area to the size of the pushrod was not optimal, and the system was very inefficient, with very little energy being transferred to the block. This resulted in the need to drive the actuator for longer in order to get a signal at the

receivers. With a more optimal clamping design these run lengths will decrease significantly. We show results for the non-optimal clamping in the next section

### Examples

The source was inserted in a hole cored in a granite block and the clamps were pressurized to 3.4 bar (50 psi). The actuator was run for 5, 20, and 80 seconds, and for each run signals were recorded at 5 accelerometers. One was directly mounted on the source to give some measure of the signature and four were mounted on the block: three on the sides and one on the bottom. The actuator was driven at low amplitude (to be certain of not exciting resonances) with a 1023 PRBS sequence where the pulse spacing was 1ms. The received signals were processed using cross correlation with the reference coded waveform.

Figure 1 shows the signal recorded by the accelerometer mounted directly on the source after processing. There is a clear impulse shape; this is what we would expect to see at the accelerometers in the block.

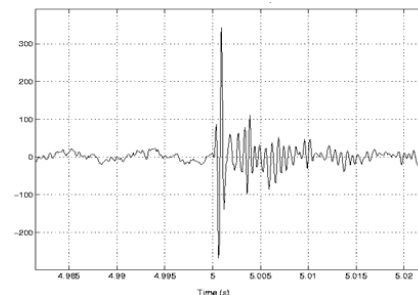


Figure 1 source signature recorded on the tool after correlation.

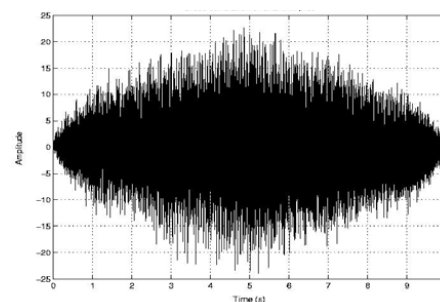


Figure 2 correlated signal from accelerometer mounted in top of the block.

### Magnetostrictive borehole source

Figure 2 shows that a 5 second run does not produce enough gain to pull the signal out of the noise. This is due mainly to the poor efficiency of the initial setup. Figure 3 shows the result of running the source for 20 seconds. This is a correlated recording from the same accelerometer as Figure 2; some structure is apparent. The unusual comb-like structure arises from the processing; the reference signal is made up of a sequence of coded continuous waveforms; as we cross correlate, each waveform produces a partial correlation until we are correlating the whole reference signal with the whole of the recorded signal. this occurs at 20sec for a 20sec long run, and this gives the maximum processing gain.

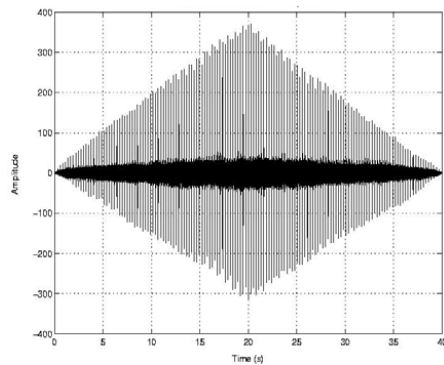


Figure 3 result of running the source for 20 seconds.

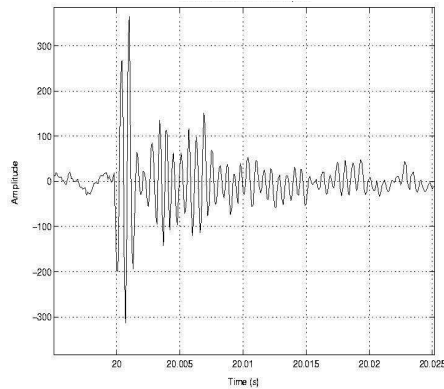


Figure 4 central peak in Figure 3, showing clear arrival.

Figure 4 , shows that if we run the source for 20 seconds we get a clear arrival; compare this with the wavelet from Figure 1, they have similar shapes but there is still some noise present even after running for 20 seconds. No signals are visible at the accelerometer in the bottom of the block.

Figure 5 shows the result of running the source for 80 seconds. This is the same receiver as Figure 4. The signal lies well above the noise, note the increase in amplitude of the first peaks. The first arrival is similar to the signal recorded on the tool (Figure 1).

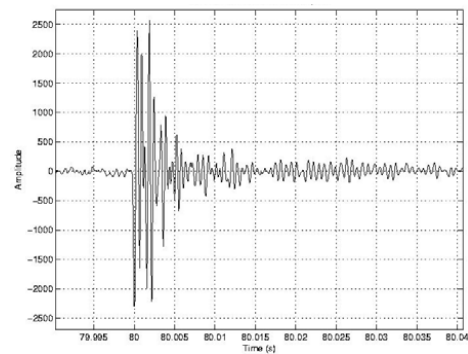


Figure 5 result for 80 second run, top accelerometer.

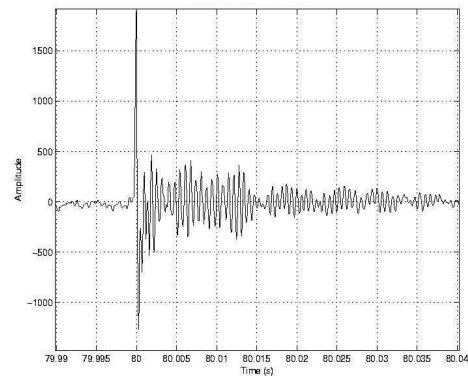


Figure 6 cross correlated result from the accelerometer in the bottom of the block for run length of 80 seconds showing clear first arrival.

### Magnetostrictive borehole source

Figure 6 is a correlated recording from the bottom of the block. There is a clear arrival which lies well above the noise. No signals were observable here for previous run lengths. This illustrates the power of running the source for a longer time. We hope to be able to achieve this result for a much shorter run time by modifying the clamping setup in order to increase the amplification of the input signal.

#### Conclusions

We have built and tested a prototype downhole source suitable both for wireline and while drilling applications, including but not limited to, single well imaging, crosswell imaging and look-ahead-of-the-bit applications. The source is built around a magnetostrictive transducer which is driven by a coded continuous waveform at low amplitudes to overcome the resonance problems that plagued previous attempts to use a magnetostrictive source in a borehole. Our design is the subject of a patent application (UK Pat App 0424808.4).

We have demonstrated that the new driving method and data processing strategy allow us to identify clear arrivals at accelerometers mounted around the block, despite driving the source at very low amplitudes. The current set up of the source is inefficient due to the sub-optimal ratio of the push rod area to the clamping area. We are working on developing a new clamping arrangement to rectify this. We are also investigating the best way of clamping the source in cased and uncased wells, and in hard and soft formations. This includes looking at different materials for the clamp shoes and investigating whether to use a smooth or a rough surface.

The next step after mechanical modifications is to put the source in a test hole and assess its performance in a field environment. We are also interested in using source signature deconvolution as an additional step to improve the data quality.

We expect that this source with the appropriate modifications will be suitable for single well and cross well applications. We believe that further development and use of this tool can lead to a step change in the quality and usability of data collected from single-well imaging experiments. It should also be suitable for integration into the drill string due to its low weight, slim dimensions and low power consumption.

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## Source signature deconvolution for VSP applications

Brendan Walsh, Anton Ziolkowski, Steve McLaughlin, Edinburgh University, Holger Mathiszk and Graham Gaston, Baker Hughes Inteq, Celle

### Summary

This paper presents the application of source signature deconvolution for improving the resolution of VSP data and removing shot-to-shot variations. The method has low complexity and requires minimal changes to current deployment and acquisition practices, and is applicable for land and marine surveys. We have applied the algorithm to vertical incidence offshore data. The method successfully removes shot-to-shot variations, and compresses the wavelet to zero-phase, improving the resolution of the data and uncovering events which were hidden by the long air-gun signature. We suggest this method should be adopted as a routine processing step in all VSP surveys, although the technology will be of greatest benefit in time-lapse experiments

### Introduction

Source signature deconvolution is routinely employed to improve the resolution of VSP data and its usefulness is understood and accepted. However, the correct method of application is rather less well understood. The processing steps known as source signature deconvolution and VSP deconvolution are described below.

In the first instance the signature from the near field hydrophone is recorded and a filter is found that converts this to a desirable wavelet, generally zero-phase; this filter is then convolved with the recorded data, with the objective of replacing the source signature with the desired wavelet. This cannot work, as the signal received at the geophones is significantly different in shape from the near field signature. This is obvious from a cursory inspection of the data. A filter which converts the near field signal to a desired wavelet will perform poorly on data recorded in the far-field, with the result that the first break will be incorrect. We illustrate this with real data.

VSP deconvolution, as described in detail by Ross et al. (1987), uses a source signature extracted from the VSP data itself, after separation into up and down going wavefields. Usually the down going P-wavefield is used, a moveout correction is applied, and the traces are stacked. An arbitrary window is then chosen around the first break and the wavelet inside this window is said to represent the source signature. It is well known that the source signature can vary considerably over the course of a VSP survey, due to towing depth, air gun leakage, and weather conditions. In this method if any variations are present they will be irretrievably mixed together resulting in a wavelet which

bears little resemblance to the true signature for each shot. Again, a filter which converts this signature to a desired wavelet will have unpredictable results on the different wavelets present in the data and could introduce artifacts which may result in an incorrect first break pick. If the signature changes the effect on each trace will be different. This lateral change in wavelet shape could be incorrectly attributed to the geology.

The application of source signature deconvolution to surface seismic data is described by Ziolkowski et al. (1998). Our method extends the approach to VSP data recorded with an air-gun source, and avoids the problems associated with the aforementioned approaches by constructing the far-field wavelet from the measured near field signature. This is straightforward in practice if the geometry of the near field phone is well known. Once the far-field signature has been constructed, this signature is used to construct the desired wavelet. (Normal practice uses a four point trapezoid in the frequency domain to define a zero-phase time-domain wavelet, which bears little relationship to the real data). The next step is to compute a deconvolution filter. This step is similar to current practice, but with the difference that all variations due to the source signature have been removed, and no additional variations have been introduced.

We illustrate the effectiveness of this approach by deconvolving one shot from a marine VSP survey and comparing the results to that obtained by using the near field recording as the source signature, which is the conventional approach.

### Theory and methodology

The situation can be visualized as shown in Figure 1; the signature recorded at the near field phone is composed of the direct arrival that travels a distance  $r$ , and the reflected arrival which travels a longer distance  $R$ . An example of a near field signature can be seen in Figure 2. The direct arrival dominates the recording; the reflected arrival is present but is much lower in amplitude due to its longer path length.

As the receiver is moved further away the path length of the reflected wave approaches that of the direct wave, thus both experience a similar amount of attenuation due to spherical divergence. The zone referred to as the far-field is reached when the amplitude of the reflected wave is approximately equal to the direct wave, giving the characteristic far-field shape shown in Figure 3.

### Source Signature VSP deconvolution

The far-field signature can be constructed from the direct wave and the sea surface reflection.  $1/r$  spherical divergence is assumed and source array directivity is ignored. This is valid for the small air-gun arrays used in VSP work.

We can obtain the direct wave by deghosting the near field signature. The far-field wavelet can then be constructed by adding back in an appropriately delayed and scaled reflection to the deghosted near field. The Fourier transform of the pressure recorded at the near field hydrophone is, from Ziolkowski (1998),

$$P(\omega) = S(\omega) \left[ \frac{1}{r} \exp\left\{i\omega \frac{r}{c}\right\} - \frac{1}{R} \exp\left\{i\omega \frac{R}{c}\right\} \right]. \quad (1)$$

Rearranging recovers the deghosted source signature  $S(\omega)$

$$S(\omega) = \frac{P(\omega)}{\left[ \frac{1}{r} \exp\left\{i\omega \frac{r}{c}\right\} - \frac{1}{R} \exp\left\{i\omega \frac{R}{c}\right\} \right]}. \quad (2)$$

Extrapolation to the far-field is achieved by putting the hydrophone at a distance  $r_f$  far below the gun:

$$F(\omega) = S(\omega) \left[ \frac{1}{r_f} \exp\left\{i\omega \frac{r_f}{c}\right\} - \frac{1}{R_f} \exp\left\{i\omega \frac{R_f}{c}\right\} \right]. \quad (3)$$

The next step is to construct a zero-phase wavelet from the far-field signature. This is done by fitting a smooth curve to the amplitude spectrum of the far-field signature. This ensures that the desired wavelet is directly related to the source signature and improves the performance of the filter on the recorded data. The smooth curve is transformed back to time and the real part is the zero-phase wavelet.

This wavelet forms the desired output for an optimum least squares Wiener shaping filter with the extrapolated far-field signature as an input. The resulting filter can then be convolved with the data to yield a deconvolved zero-phase record. Berkhout (1979) showed that the zero-phase wavelet is the shortest possible in a given bandwidth. Thus deconvolution to zero-phase gives the best resolution in the given bandwidth.

If the signature varies from shot to shot, a new filter must be computed for each shot. It is important that this is done before stacking. Application of the deconvolution filter in this case removes all shot-to-shot variations.

In summary, the processing flow is as follows:

- Deghost the near field recording.
- Extrapolate to the far-field by scaling, delaying, and adding in the sea surface ghost.
- Use the far-field signature to construct a desired zero-phase wavelet.
- Find the optimal filter which converts the far-field signature to the desired wavelet.
- Convolve this filter with the data for the same shot, to collapse the source signature and improve the resolution.
- Keeping the desired wavelet constant, compute a new deconvolution filter for each shot.
- Application of the filter on a shot-by-shot basis removes all shot-to-shot variations.
- The data can now be stacked to attenuate incoherent noise

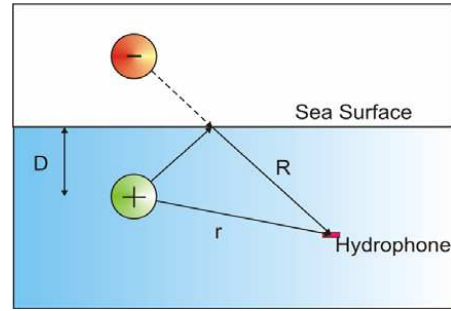


Figure 1 The virtual source method for determining path lengths traveled by direct and reflected waves.

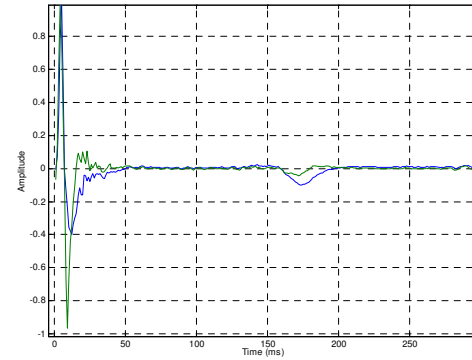


Figure 2. Near field signature over extrapolated far-field signature with propagation delay removed.

# Source Signature VSP deconvolution

## Examples

We used our source signature deconvolution method to process data from an offshore vertical incidence VSP shot by Baker Atlas. The quality of the near field recording was very good and the geometry of the hydrophone was known precisely. We then deconvolved the same trace using the near field source signature and compared the results.

Figure 3 shows the vertical component before deconvolution: the first arrival is well defined and the wavelet shape is similar to that of our extrapolated wavelet. Figure 4 shows the zero phase wavelet which was constructed from the amplitude spectrum of the extrapolated far field signature. This forms the desired output for the Wiener shaping filter. Figure 5 shows the same trace as Figure 3 after source signature deconvolution. We can see that the characteristic far-field arrival shape has been replaced by a wavelet which looks much more like the desired wavelet of Figure 4. Comparison with the recorded signature show the first break has moved to the first peak and that there are a couple of event visible now that were obscured before. Also note that the bubble pulse at 1.85 sec has been removed.

Figure 6 shows the result of using the near field source signature in place of the far-field signature and using a four point trapezoid, with values of 4.0,8.0-80.0, 96.0 Hz to define the desired zero-phase wavelet.

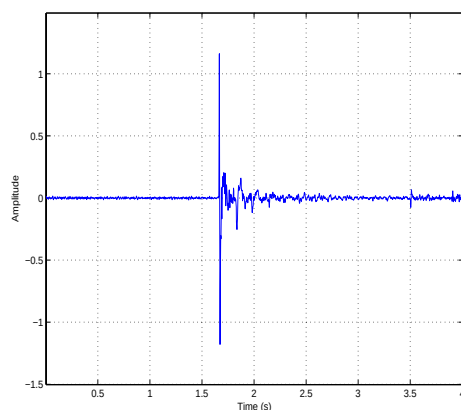


Figure 3 A raw vertical component recording.

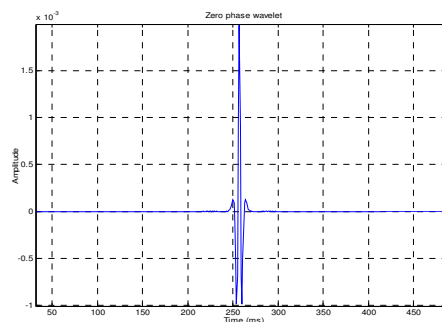


Figure 4 the desired zero phase wavelet

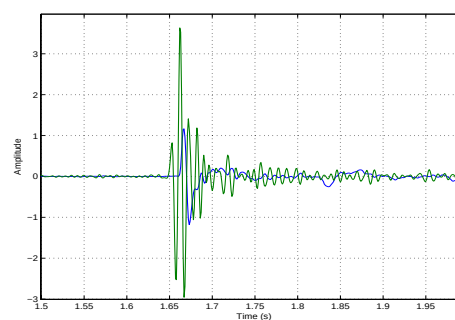


Figure 5 the deconvolved z component (green) over the raw z component (blue). The shows the first break as the first main peak of the deconvolved trace.

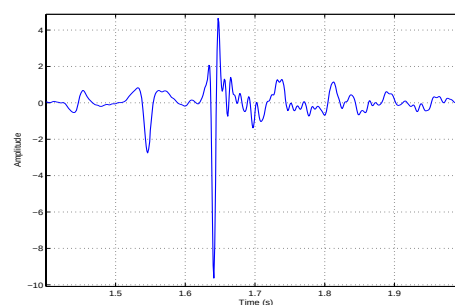


Figure 6 the result of deconvolving the raw trace with the near field deconvolution filter.

### Source Signature VSP deconvolution

We can see that the filter does an apparently good job of sharpening up the first arrival. But it seems to introduce artifact at around 1.55ms before the first arrival and there are no clear events after the first break. Also the wavelet shape has not changed very much: it does not look like a zero-phase wavelet, and comparison with the raw data shows that the first break (taken to be the first significant peak) is in error by 5ms. In this case we used a near field signature and a raw signature from the same shot, so this is a best case scenario.

If we were to apply this to a whole dataset of, say, 1000 traces, and display all the traces together, the data would probably look very good with a clear first break, however it would be in the wrong place, and any velocities derived from the data would be in error.

In order to illustrate how well our source signature deconvolution method performs, we have deconvolved 11 vertical component records that show very different first arrival shapes. The traces have been chosen at random from the dataset. Figure 7 shows the raw traces; the first three are from close to the well head and show strong casing arrivals and some superimposed rig noise. Figure 8 is the result after deconvolution: all signature variations have been removed and the first break is clearly visible as the large peak on all the traces, this resembles very closely the desired wavelet.

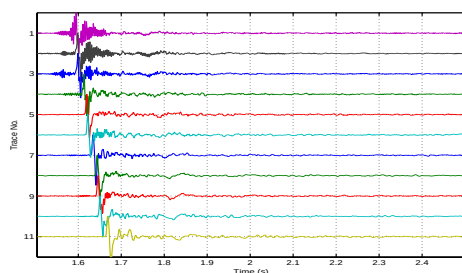


Figure 7 raw vertical component.

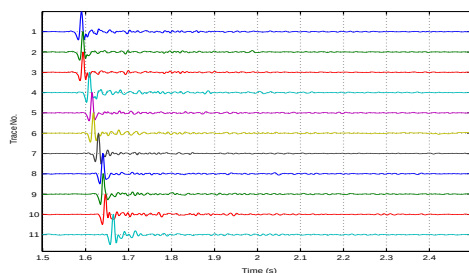


Figure 8 deconvolved vertical component

### Conclusions

We have presented a new method to deconvolve marine and land based VSP data. It uses the recorded source signature to remove all shot-to-shot variations and transforms the data to zero-phase, compressing all events and separating overlapping arrivals.

The algorithm is straightforward and could easily be implemented in any current processing setup; this method makes it unnecessary to guess the wavelet from the down going wavefield or to assume that the near field signature approximates the wavelet seen in the far-field.

It would be desirable to know the recording characteristics of the receivers used, i.e. frequency response curves and any additional filters used. If this was known then the sensitivities of the receivers could be normalized and the true amplitude of the data preserved. This is an important consideration for a time-lapse survey or if AVO is important.

We have demonstrated that this method can remove shot-to-shot variations, compress overlapping arrivals, and remove environmental artifacts such as rig noise.

We have compared our method with the current practice and it is clear that using a near field source signature for deconvolution introduces artifacts and errors into the data. Instead this signature should be extrapolated to the far-field and a zero-phase wavelet constructed from this signature. It is this far-field wavelet which should be used to find a deconvolution filter.

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### Acknowledgements

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## Appendix B

# Patents

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- A. Ziolkowski, S. McLaughlin, B. Walsh, J. Dripps, and A.Brand, “Improvements to Seismic Sources; UK Patent Application No 0424808.4, filed 10/11/2004
- B. Walsh, S. McLaughlin, A. Ziolkowski, “Vertical Seismic Profiling Method; UK 0511678.5, filed 08/06/2005

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## Appendix C

# Application of EMD to VSP data

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This appendix describes the algorithm used to obtain the IMFs in the EMD technique, as described in Chapter 3. In addition results from the application of the technique to marine VSP data are also presented.

The EMD technique can be described by the following algorithm which follows Magrin-Changnolleu and Baraniuk [49].

1. Initialize  $r_o(t) = x(t), i = 1$
2. Extract the  $i$ -th IMF:
  - (a) Initialize  $h_0(t) = r_i(t), j = 1$
  - (b) Extract the local minima and maxima of  $h_{j-1}(t)$
  - (c) Interpolate the local maxima and the local minima by a cubic spline to form upper and lower envelopes of  $h_{j-1}(t)$
  - (d) calculate the mean  $m_{j-1}(t)$  of the upper and lower envelopes
  - (e)  $h_j(t) = h_{j-1}(t) - m_{j-1}(t)$
  - (f) If the stopping criterion is satisfied then set  $imf_i(t) = h_j(t)$  else go to (b) with  $j = j + 1$
3.  $r_i(t) = r_{i-1}(t) - imf_i(t)$
4. If  $r_i(t)$  still has at least two extrema then go back to 2 with  $i = i + 1$  else the decomposition is finished and  $r_i(t)$  is the residue.

When the algorithm finishes we are left with the following:

$$x(t) = \sum_{i=1}^n imf_i(t) + r_n(t) \quad (C.1)$$

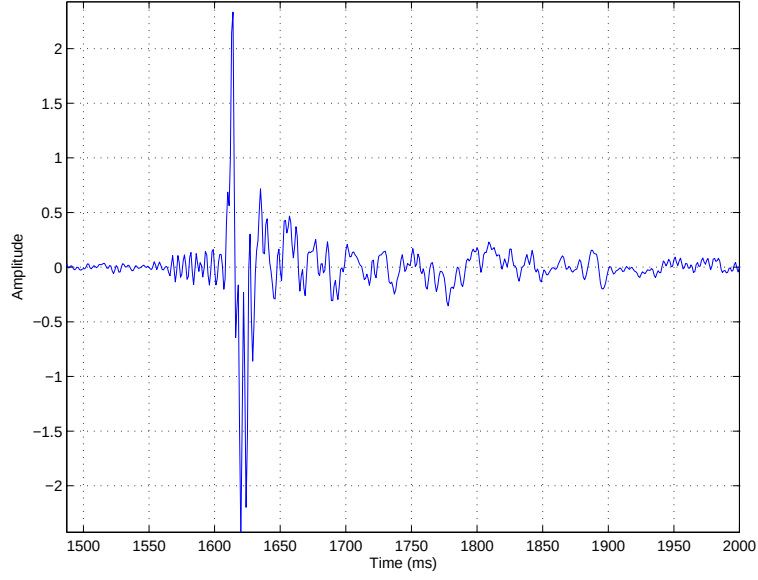


**Figure C.1:** *Noisy axial component trace, taken from a marine VSP record*

where  $r_n(t)$  is the residue of the decomposition.

Essentially EMD works by picking out the highest frequency oscillation that remains in the signal. Therefore, the frequency content of each successive IMF is less than the one that went before.

Figure C.2 is the result of applying the EMD algorithm to a noisy data trace from a marine VSP experiment as shown in Figure C.1. Figure C.3 shows the processed trace overlying the raw data it can be seen that the 13th IMF succeeds in completely removing most of the noise that overlies the signal and as a result the first break is much easier to pick.

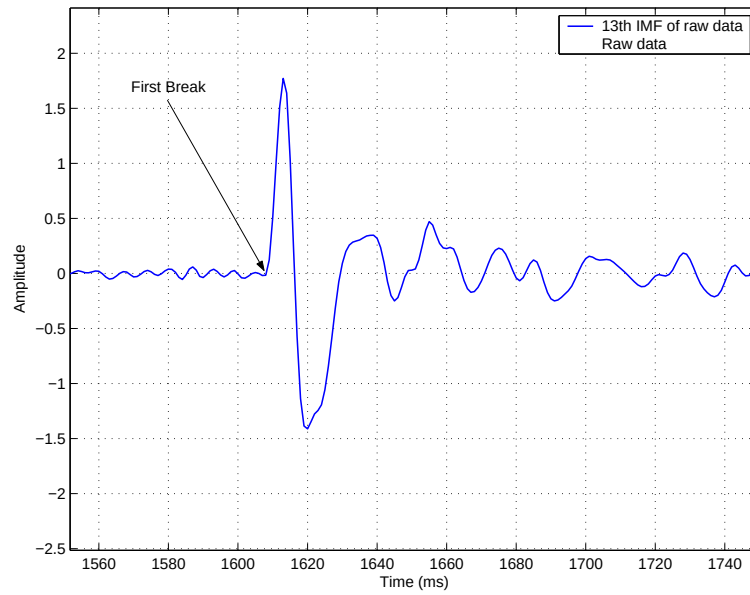


**Figure C.2:** The result of applying the EMD technique to the trace in Figure C.1

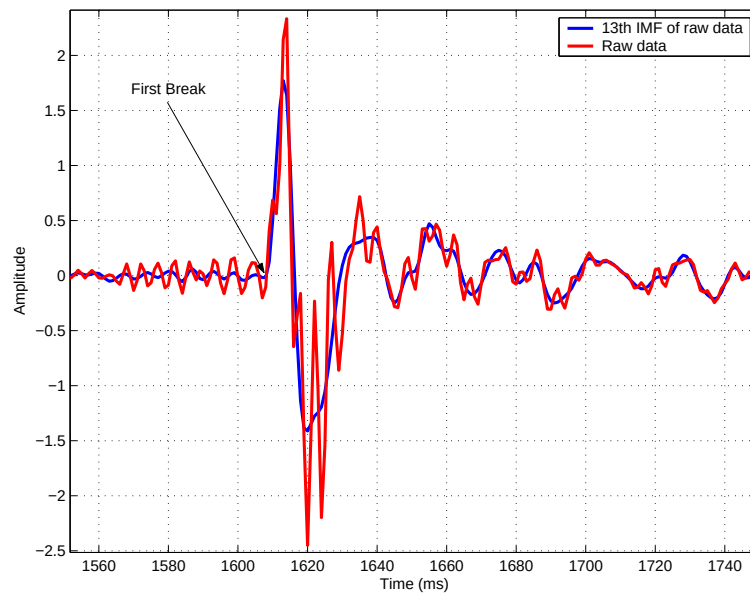


**Figure C.3:** Processed trace plotted over the raw trace highlighting the first break.

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