Investigation and optimization of OBC sensor array coupling to the seafloor

Novel approach to systematic testing of receiver coupling

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Dissertation for the degree philosophiae doctor (PhD)
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„Kausalität ist immer eine Abfolge von Ursache und Wirkung at infinitum.
Hierbei ist nie ein Objekt Ursache.
Es ist immer ein Zustand.
Es gibt drei Arten von Kausalität: Ursache, Reiz und Motiv“

Schopenhauer

Scientific environment

My work presented in this dissertation was carried out during my PhD study from September 2010 to July 2013 at the Department of Earth Science, University of Bergen (UiB). This thesis was a part of the Norwegian Research Councils (NFR) Industrial PhD (Nærings PhD) program and partly funded by Octio AS. The supervisor of this project was Professor Rolf Mjelde and the co-supervisors were Leon Løvheim (Octio) and Jan Petter Fjellanger (Statoil).

This dissertation is organized into two complementary parts. The first part gives a general overview of the encountered problems of seismic receiver coupling to the seafloor along with the strategies how to overcome these problems. During this first part I will introduce the problems and give a review and the leitmotiv of the four papers, which deal with different aspects of receiver coupling to the seafloor.

The second part, which contains the main outcome of my research, is a collection of four research papers and four expanded abstracts. The research papers, which are submitted to different scientific journals, will be referred to numerically as 1-4 and the expanded abstracts will be given capital letters I-IV.

The preliminarily results of paper 1 was presented at the AGU conference 2011 and in more detail at the SEG conference 2012, and the paper is currently under review in the 'Geophysical Prospecting' journal. The preliminarily results of paper 2 were presented at the SEG conference 2010, and is submitted to 'Geophysical Prospecting' journal. The simulation results of receiver coupling in paper 3 is submitted to the 'Geophysics' journal. Finally, the fourth paper is submitted to the 'Geophysics' journal.

Acknowledgements

This thesis, entitled "Investigation and optimization of OBC sensor array coupling to the seafloor", has been submitted for the degree of philosophiae doctor (PhD) at the University of Bergen (UiB), Norway. The research was carried out from September 2010 to July 2013 at the Department of Earth Science (UiB) and Octio AS, Norway.

I would like to express my gratitude to my supervisors Professor Rolf Mjelde, Jan Petter Fjellanger, Jakob Haldorsen, Fred Duennebier and my former colleagues at Octio AS. I would in particular like to thank Annette Linda Vestlund from the NFR for her help in making financing until the end possible. Furthermore, I would especially like to thank Rolf Mjelde for his support, quick responses to any of my questions and his help in finishing this thesis.

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Marcus Landschulze Bergen, October 2013

Abstract

The most important challenge for the oil-industry is to increase the recovery rates for existing oil and gas fields and to map fluid movements with time-lapse 4D seismic, ensure caprock integrity and reduce geo-hazards or to monitor CO_2 storage in an offshore reservoir by using active and passive sources (e.g. Airgun-survey and passive seismic/microseismic). The common seismic equipment is configured in receiver lines with cables trenched or covered on the sea-bottom.

The equipment typically comprises up to 4000 receivers depending on the aerial extent of the reservoir. Multicomponent receiver technology like Ocean Bottom Cable (OBC), borehole tools or Ocean Bottom Nodes (OBN) provides information on both pressure and particle velocity recorded with three component accelerometers or geophones and an omnidirectional hydrophone at the seafloor level, allowing complementary PP and PS imaging. In order to improve the 4C seismic processing by reducing noise and perform high accurate shear-wave measurements, it is important to understand the coupling of a receiver array to the seafloor.

This thesis is focusing on several aspects of receiver coupling to the seafloor by presenting two developed methods on how to measure coupling and how to estimate receiver performance or vector fidelity (paper 1 and 2). The results from these methods are used to simulate receiver coupling by using finite element methods (software tool Multiphysics) to investigate the full waveform outside the receiver housing (paper 3). During my research I discovered different responses of seismic signals depending on the azimuth between the receiver and the source (paper 4). I thus investigated measured data and compared it with synthetic/simulated data and developed one possible explanation to why receiver coupling is azimuth depending.

List of publications

Paper 1: Landschulze, M, Mjelde, R. (2013): "Horizontal OBC coupling to sediment; an iterative method to estimate coupling parameters"

Submitted to Geophysical Prospecting 11-Mar-2013; under review

Paper 2: Landschulze, M, Mjelde, R. (2013): "Qualitative seismic receiver array performance and coupling estimation, a method using ambient noise"

Submitted to 'Geophysical Prospecting' 08-July-2013; *under review*

Paper 3: Landschulze, M, Mjelde, R., Landschulze, K. (2013): "Systematic simulation of multicomponent receiver coupling to the seafloor; using rheological models"

Submitted to 'Geophysics' 02-September-2013; under review

Paper 4: Landschulze, M, Mjelde, R. (2013): "Azimuth-dependent OBC receiver coupling to the seafloor"

Submitted to 'Geophysics' 02-September-2013; under review

Expanded Abstracts:

I Qualitative seismic sensor array estimation and seafloor coupling by using incoherent ambient signals for reservoir-monitoring systems

SEG 2010 (Oral)

II Estimation of OBC coupling to the seafloor using 4C seismic data

SEG 2012 (Poster)

Abstract:

III Horizontal Ocean-Bottom-Sensor sediment coupling; Estimation of coupling parameters from seismic data

AGU 2011 (Oral)

Contents

Note to the readers

As an advice to readers not accustomed to the Norwegian style of cumulative doctoral dissertations, this is a short guide to the structure of such a thesis. Contrary to monographic dissertations, Norwegian doctoral theses in the natural science usually consist of research papers published in or submitted to peer-reviewed journals with international impact framed by an introduction and final chapter. While the introduction presents the objectives of the research as well as the existing literary framework in which the dissertation is embedded in, the final chapter concludes and shortly discusses the overall results of the research.

The articles included in the thesis as separate chapters represents stand-alone publications and therefore overlap to a certain extent. In order to enable evaluation of the candidate's contribution to the presented research, an authorship statement is included in the text section, following the requirement for PhD theses at the University of Bergen.

Authorship Statement

As required by the regulation of the University of Bergen regarding cumulative PhD theses, the following author statement is given to specify the extent of contribution of the involved authors for each publication. The four papers presented in this thesis are all joint publications, where the candidate is the first author and principal investigator on all four. Consequently, the responsibility of possible omissions or misinterpretations remains with the candidate. An overview of the candidates main contribution is given below.

Paper 1: Landschulze, M, Mjelde, R. (2013): “Horizontal OBC coupling to sediment; an iterative method to estimate coupling parameters”

The candidate was responsible for data collection, simulation, method development, data processing, writing and figure drafting. All authors performed manuscript reviews.

Paper 2: Landschulze, M, Mjelde, R. (2013): “Qualitative seismic receiver array performance and coupling estimation, a method using ambient noise”

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Paper 3: Landschulze, M, Mjelde, R., Landschulze, K. (2013): “Systematic simulation of multicomponent receiver coupling to the seafloor; using rheological models”

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The candidate was responsible for data collection, simulation, method development, data processing, writing and figure drafting. All authors performed manuscript reviews.

1. Introduction

Multicomponent receivers are used to provide information on both pressure and particle motion measured on the ground. This allows complementary 3D PP and PS imaging. The poor quality of ocean bottom seismic data is mainly caused by different signal responses on the two horizontal receiver components. The vertical coupling to the seafloor is well understood by using damped oscillation spring systems, called Kelvin-Voigt model, to simulate the amplitude and phase as a function of frequency (e.g. Duennebier et al., 1995). But today, most of the coupling investigations consider only the vertical component instead of all 3 sensor-components as a unit.

The offshore receiver coupling is more critical than for land systems because of different coupling conditions to control. The topmost couple of meters sediment below the seafloor is a mixture of a solid phase (minerals, organic matter), a liquid phase (in general water) and sometimes a gas phase (methane, carbon dioxide). These phases combine to a solid structure, skeleton or fabric with relative high shear-strength and a pore-fluid without any shear-strength. The solid- and the time-scale of the liquid phase flow govern the sediment behavior, and with that the coupling between sensor-housing and seabed (see Winterwerp et al., 2004). Trenching can improve receiver coupling to the seafloor, but is not always applicable due to installation costs at large water depth.

Poor sensor coupling with the seafloor produces resonances and phase distortions. Figure 1 shows the RMS surface plot from the direct-wave measured during an air-gun survey. The bin-grid was 12.5 x 12.5 meter. The top-left plot shows the inline component with relatively poor coupling, whereas the top-right plot presents the crossline component. We can conclude that the coupling to the soft sediment is poor, due to the fact that the RMS amplitude is not equally distributed along the inline and crossline. The left "eight"-shape part has less amplitude and a different shape than the right "eight"-shape part. Both bottom plots show the vertical component and the hydrophone with the expected good coupling represented in a round shape for the RMS amplitude.

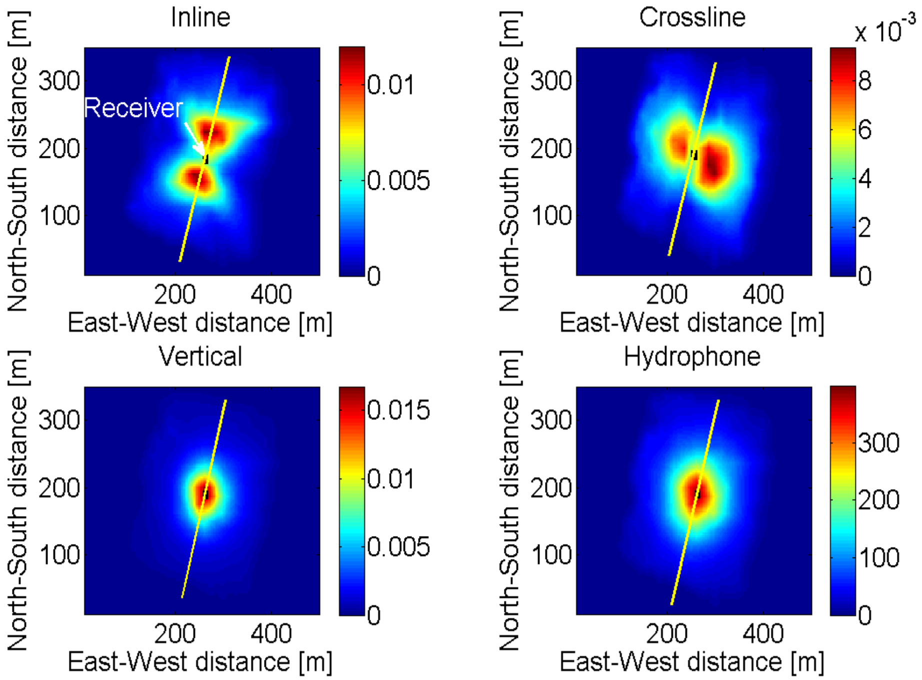


FIGURE 1 RMS SURFACE PLOT FROM THE DIRECT-WAVE FROM A SPECIFIC NODE IN THE RESERVOIR- FOUR COMPONENTS

Figure 2 illustrates the OBC coupling in a hodogram for a horizontal receiver component. The diagram shows the data results from a trenched OBC in soft sediment. A 45 degree shot-position to the receiver was selected for this diagram. This means that both horizontal components should be similar, and the hodogram should show a straight line with 45 degree angle. Since this is not the case here, we can conclude that the receiver coupling to the seafloor is poor.

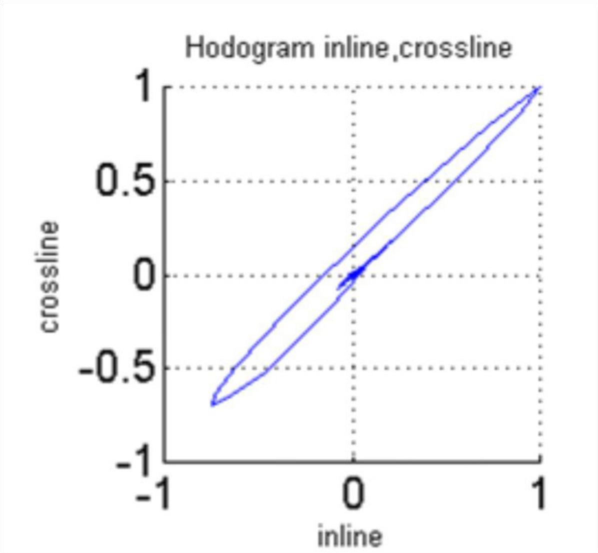


FIGURE 2 NORMALIZED RECEIVER HODOGRAM COMPARING THE INLINE AND CROSSLINE RECEIVER COMPONENTS.

Shear wave processing of 4C seismic data involves the analysis of the horizontal particle motion. This analysis requires that the inline and crossline measurements must be similar to the particle motion both in sensitivity and frequency response. It is well known that there is a difference in the frequency response of the horizontal and vertical detectors (e.g. Gaiser, 2007). These differences in the frequency response in OBC surveys can cause problems for multi-component processing.

An improvement of receiver coupling to the seafloor will increase the data quality and make multicomponent arrays more sensitive for microseismic and passive seismic, as well as for active seismic surveys. This is an important advantage with respect to subsidence above a reservoir (e.g. on Ekofisk). Micro and passive seismic methods could be used as an indicator for caprock integrity problems, or to monitor fluid movements from e.g. injected water or supercritical CO2.

In order to improve receiver coupling in the offshore environment, novel and systematic approaches are needed. Today several approaches exist for the vertical component of a three component sensor (e.g. Duennebier et al., 1995, Fjellanger et al., 2002), but there are only a few systematic investigations for the horizontal components. Most of the vertical component approaches use special pre-processing methods like separation of up-going and down-going P and S wave-fields (Edme et al., 2005) or inverse filtering (Dellinger et al., 2001). But in order to understand the receiver coupling to the seafloor, it is essential to investigate the sensor coupling itself.

For a systematic investigation, it is substantial to understand the interaction between the receiver and the surrounding sediment. First of all the coupling mechanism has to be identified. The mechanical coupling between the receiver housing and the sediment can be described as a low-pass filter with a resulting resonance frequency set by the coupling (e.g. Winterwerp et al., 2004, Duennebier and Sutton, 1995, Vos et al., 1995).

The objectives of this PhD thesis are to improve the understanding of receiver coupling to the seafloor in general and develop a method to estimate the coupling parameters in particular. These objectives can be summarized to: (1) examine a method to estimate the receiver performance and the coupling to the seafloor in the frequency domain, (2) develop another robust method which can describe sensor coupling to the seafloor and (3) investigate possible differences in coupling parameters for inline and crossline components due to varying deployment methods and the shot receiver azimuth dependency. In order to understand receiver coupling we designed a simulation workflow of three viscoelastic models to investigate (4) the coupling behavior for different coupling parameters, (5) the coupling receiver responses, (6) possible differences between up-going and down-going waves and (7) the wave-field response to the viscoelastic coupled receiver housing.

The first paper presents a method for estimating the two coupling parameters, resonance frequency and damping-ratio, in an “iterative loop”. This iterative loop method, called Sensor Coupling Estimation Method (SCEM), uses the “coupling free” hydrophone signal convolved with the coupling transfer function. The resulting mathematically coupled hydrophone signal will be correlated with one horizontal or vertical component. If the correlation is high, the resulting coupling parameters represent the sensor coupling. The advantage of this method is that it provides a qualitative estimation of the coupling parameters, which can be used for example to elucidate azimuth depending coupling. Figure 3 shows the resonance frequency and damping-ratio of an active seismic survey, where the coupling parameters are plotted at the source position. The “northern” part of the survey area indicates a lower resonance frequency compared to the “southern” part. The damping-ratio indicates the opposite behavior: Higher damping-ratio in the “northern” part and lower in the “southern” part. These results are not fully understood and are still part of my investigation, but these observations might give an indication of coupling changes at or just below the seafloor.

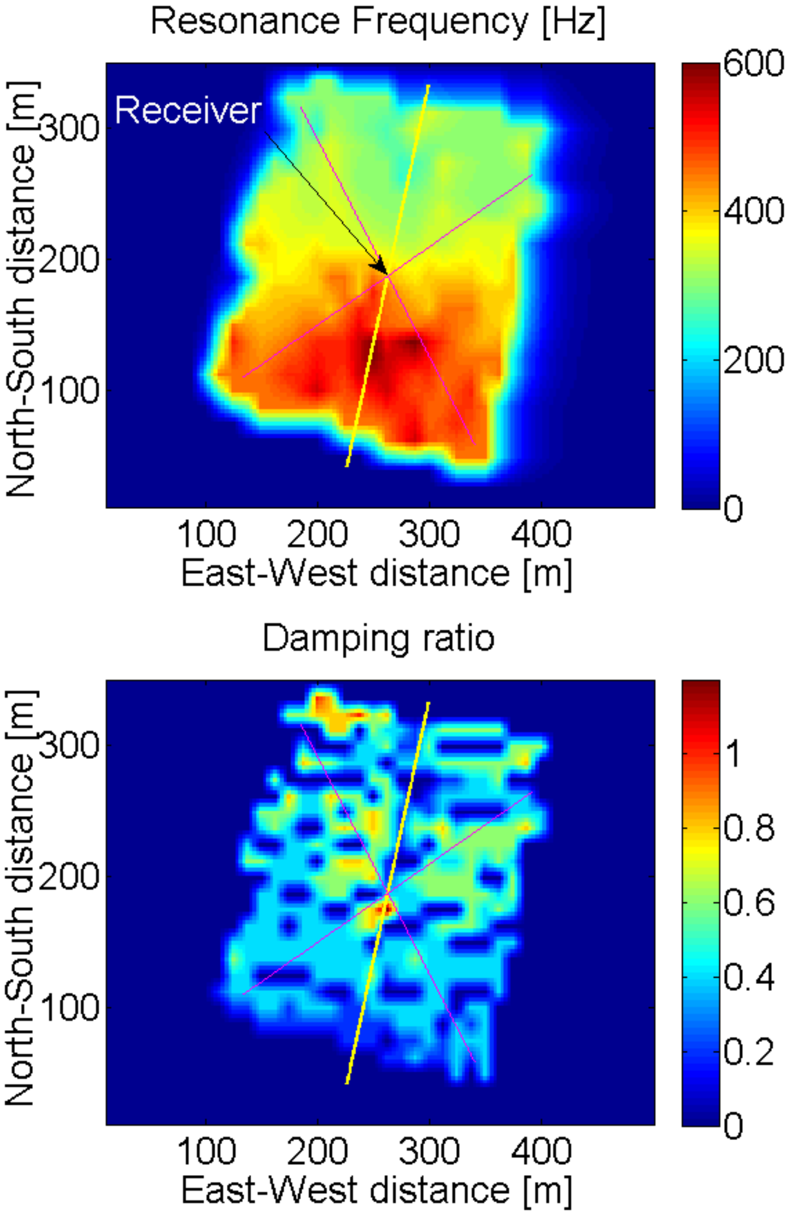


FIGURE 3 SHOWS CHANGES IN THE COUPLING PARAMETERS DEPENDING ON THE SHOT POSITION OF AN ACTIVE SEISMIC SURVEY. THE COLOR CODE IS THE RESONANCE FREQUENCY IN HZ AND THE DAMPING RATIO, RESPECTIVELY.

The second paper of this thesis concerns the evaluation of the receiver coupling as a pre-survey quality control of receiver arrays. Receiver attribute analysis and calibration are becoming powerful methods for evaluation and calibration of seismic receivers. However, typical reservoir monitoring arrays often comprise several thousand receiver-nodes, which can make quality checking of all receivers in an array a time consuming and costly procedure. Nevertheless, the reliability of the receivers is crucial and has to be proven before each survey. This paper describes a method called: Qualitative Seismic Sensor Array Estimation (QSSE), which is a method to estimate the different receiver responses as a pre-survey quality control (QC) and the receiver coupling to the ground in the frequency domain. The significant benefit of the QSSE method is that it provides a qualitative measurement of the amplitude and phase response of the frequency-band of interest before a survey starts or after installation of a receiver or array. The method extends information about the ground coupling by comparing two receiver components, neighbors or against a reference receiver.

In order to understand receiver coupling to the seafloor three approaches are possible. The first one is to rebuild the seafloor in a laboratory in a water tank and include the receiver into it. This gives control over the environment, but with the drawback of higher source signal frequencies to avoid unwanted tank boundary reflections. Furthermore, these higher frequencies will have a great effect on the receiver coupling and will therefore be inconclusive for the seismic frequency band of interest. Another approach is to install a test system into a “real” sediment, but then it is difficult to control the environment and this procedure will also increase the costs for installation and operation. The third approach is to simulate receiver coupling, which is the topic of the third paper.

The third paper describes a FEM simulation workflow to simulate down-going P-waves and up-going reflected P- and S-waves. The mechanical receiver coupling to the seafloor was simulated as a viscoelastic system with the combination of linear elastic springs and linear viscous dash-pots (known as rheological models). Three models cover most of all mechanical coupling systems, the Maxwell Model, Kelvin Voigt

Model and Standard Linear Solid Model. All three models are investigated and the workflow provides information about receiver coupling to the seafloor.

After a test survey in very soft bio sediment in the Husøy harbor, Norway I encountered differences in the coupling parameters depending on the azimuth between shot and receiver. Therefore I started to investigate source-receiver azimuth depending coupling in greater detail, and the fourth paper summarizes my results, comparing real data from the Husøy harbor and synthetic data. Two possible connections between the inline (X) and crossline (Y) receiver component were investigated, and the results were plotted in Coherency Spatial Visualization Plots (CSVP) and RMS Spatial Visualization Plots (RSVP). Both plots are able to illustrate spatial changes in the receiver response due to azimuth depending receiver coupling. In this paper we try to explain why there is a difference between down- and up-going waves, time delays and frequency attenuation, and why polarization analysis and presence of azimuthal anisotropy can lead to wrong results.

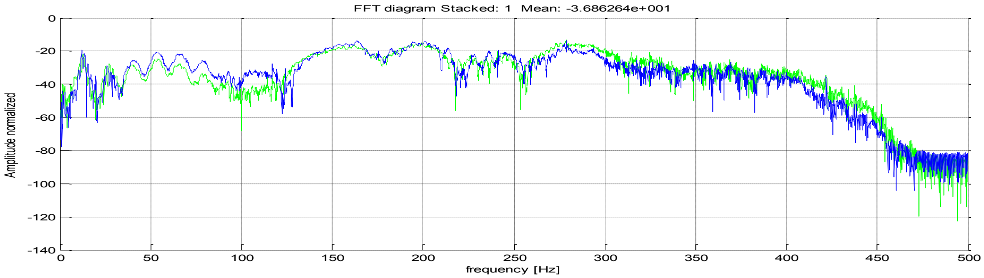
Further work

Currently, I am working on the azimuth depending coupling deconvolution of the Husøy data set, with some interesting preliminary results. Table 1 shows the polarization angle retrieved from the seismic data using Eigen-value analysis before (orange) and after (green) the deconvolution. In the far right column the azimuth is calculated from the shot receiver geometry stored in the SEG-Y header. This result shows a clear improvement compared to the raw data (yellow/orange colored columns) and reduces the coupling effects in the seismic data. The calculated azimuth is very close to the “real” azimuth (far right column with white background). In order to estimate the shot-receiver azimuth, I used the first-break to calculate the azimuth. Figure 4 illustrates the frequency spectrum of the receiver inline (blue) and crossline (green) before and after deconvolution. The ca. 20dB amplification seen in the frequency spectrum after deconvolution is not yet fully understood and may be caused by a wrongly set amplification factor in the deconvolution function. But the improvement is clearly present in figure 4b and shows similar response on both horizontal receiver components. In order to prove the reliability and robustness of the azimuth depending coupling deconvolution, more field data test are needed.

Raw data			Corrected data		Geometric Calc.
shot	**correlation**	**azimuth**	**correlation**	**azimuth**	**azimuth**
1	-0.919	-53.940	-1.000	-52.485	-52.5204
2	0.845	70.911	-1.000	-50.133	-50.1104
3	0.864	67.100	-1.000	-47.131	-47.1238
4	0.877	59.386	-1.000	-43.343	-43.3477
5	0.846	52.282	-1.000	-38.849	-38.86
6	0.751	50.343	-1.000	-33.131	-33.1481
7	0.650	47.850	-1.000	-26.505	-26.4982
8	0.657	36.150	-1.000	-18.651	-18.6427
9	0.417	19.537	-1.000	-9.248	-9.2277
10	0.521	19.669	0.998	1.512	1.525
11	0.530	12.927	1.000	13.326	13.3322
12	0.346	5.949	1.000	25.925	25.9325
13	0.023	0.944	1.000	48.647	48.6469
14	-0.602	-17.445	1.000	57.271	57.2408
15	-0.845	-30.253	1.000	63.805	63.7524
16	-0.902	-38.779	1.000	68.229	68.152
17	-0.921	-46.205	1.000	71.514	71.406
18	-0.923	-50.741	1.000	74.241	74.1028

TABLE 1 **RESULT FROM THE EIGEN-VALUE ANALYSIS SHOWING THE RAW DATA COMPARED TO THE DECONVOLVED DATA.**

a) Before deconvolution



b) After deconvolution

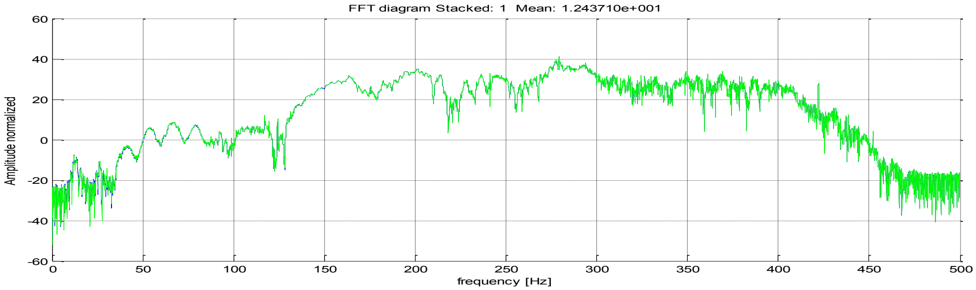


FIGURE 4 **FREQUENCY SPECTRUM OF A WHOLE TRACE FROM AN INLINE (BLUE) AND CROSSLINE (GREEN) RECEIVER COMPONENT BEFORE AND AFTER AZIMUTH DEPENDING COUPLING DECONVOLUTION.**

Furthermore, I am working on simulating receiver coupling using a 3D model in order to investigate the viscoelastic behavior in and around the receiver housing in more detail. As described in the third paper, the viscoelastic coupling disturbs the traveling wave field not like a point source, but more like a damped oscillator which generates Rayleigh waves. I hope to get a better understanding of this phenomenon with a 3D model. Figure 5 shows the preliminary 3D results with the sensor housing in the middle of the three surfaces. The mesh size with 5m is too coarse for a detailed interpretation due to computer memory issues. In order to get higher mesh size, more memory is needed (ca. 24GByte RAM).

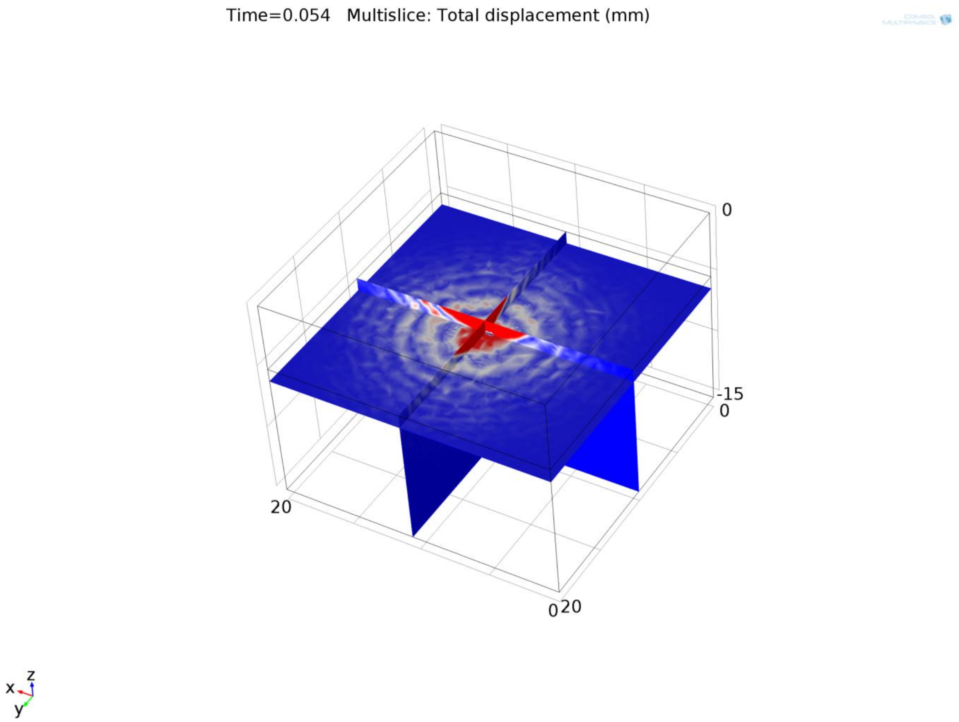


Figure 5 shows the first 3D receiver coupling results using the Kelvin-Voigt model. The mesh size is with 5m, which is too large to show viscoelastic coupling effects in this 20m by 20m by 15m cube and 20Hz Ricker source.