9. Appendix

CONFERENCE ABSTRACTS

EXPANDED ABSTRACT

SEG 2010

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

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Summary:

Seismic sensor array attribute analyses on ocean bottom cables (OBC) are becoming powerful methods for evaluation and calibration of seismic sensors. But reservoir monitoring arrays are counting several 1000 sensor-nodes and to quality check all sensors in an array is a time consuming and cost intensive procedure. Nevertheless, the reliability of the sensors is crucial and has to be proven prior to each survey. A qualitative estimation of the sensor coupling to the seafloor is a critical factor to improve the pre-processed data.

I will describe a method for Qualitative Seismic Sensor Estimation (QSSE) to estimate the different behavior between sensors in a reservoir monitoring array as well as the sensor coupling to the seafloor.

The significant benefit of this method is to get a qualitative statement about the amplitude and phase response over the frequency-band of interest before a survey starts.

The quality control (QC) of seismic data adds contributes significantly to the turnaround time of pre-processing and takes place after a survey. QSSE provides QC information prior to the survey and helps to fine-tune the seismic QC attributes or improves the data quality during pre-processing. Conventional QC practices have to handle a large variety of attributes with a priori information like RMS calculations during a survey. Instead of different types of RMS measurements in the time domain QSSE provides the sensor quality and seafloor coupling in the frequency domain in one result.

Therefore QSSE extends information about the seafloor coupling comparing two components, neighbors or each sensor with a reference sensor.

I shortly present the mathematical description of this method and some case studies to confirm the usability of QSSE.

The case studies demonstrate the usefulness of this method and that the turnaround time can be decreased because of a better understanding of the sensor behavior and the sensor coupling to the seafloor.

QSSE provides a frequency depending amplitude and phase-shift plot or a single average value for the frequency-range of interest.

Introduction

Conventional QC practices can require a large amount of efforts to reduce the pre-processing turnaround time. The data QC takes place during the survey or after but not before. Therefore some attributes have to be set by a-priori information and may be incorrect. This causes inaccurate data, e.g. too high noise floor, and is impossible to detect during the survey.

Modern seismic QC uses seismic trace attributes like energy levels, energy decay factors and RMS amplitude calculations in combination with survey positioning information to evaluate the data after each shot. To get an adequate QC estimation it is obvious that the sensor behavior has to be well known.

The presented method is a link between QC estimation and the understanding of the sensor coupling.

I will give an expression for the method in terms of frequency environment and power spectral densities, based on correlation analysis of recordings from a statistically common and random incoherent ambient noise as an input signal. This provides a compact representation of the frequency response of the seismic system.

The same approach is used since many years, but those approaches apply the sensor-transfer-function or special weighted estimator solutions (e.g. Chave et al. 1987).

The presented method is robust, compared with conventional calibration methods, and does not require a priori information about the sensor's transfer-function. The aim is to get the different sensor behaviors in a reservoir monitoring array without exact knowledge of the transfer-function.

This method can be used for all kinds of sensors or sensor-arrays. In order to estimate sensor behavior with ambient noise it is only necessary to couple the ambient noise to the sensor without resonance effects.

Method

A discrete random process sequence x(k) can be transformed into the frequency-domain (using time-discrete Fourier-transformation) to get information about the spectral characteristics. Analogously, the auto-correlation-sequence $r_{yy}(k)$ can transform a stationary random process into an auto-power-density (APD) spectrum (see eq. 1.0a) to describe the y(k) behavior in the frequency-domain.

$$r_{xx}(k) = \sum_{K=-\infty}^{\infty} x(k) \cdot x(k+\tau) \qquad (1.0a)$$

$$S_{xx}(k) = \sum_{k=-\infty}^{\infty} r_{xx}(k) \cdot e^{-j\Omega k}$$

$$S_{xx}(k) = r_{xx}(0) + 2\sum_{K=1}^{\infty} r_{xx}(k) \cdot \cos(\Omega k) \in \Re \qquad (1.0b)$$

with $e^{j\Omega} = \cos\Omega + j\cdot\sin\Omega$, $j^2 = -1$, $\Omega = 2\cdot\pi\cdot f$, $x = x_n$
n=number of sensors.

Unfortunately, equation 1.0b is real and the discrete random process sequence y(k) loses the complex part ($j\cdot\sin\Omega$). Because of that it is impossible to get the phase of $r_{yy}(k)$. The APD is only able to describe the amplitude response in the frequency-domain and the empirical auto covariance for the noise-floor. That means that the APD is a good method for quantitative amplitude description, but not qualitative; including the phase. But the cross-correlation function is able to derive the phase!

In the time-domain the cross-correlation is defined as:

$$r_{xy}(k) = \sum_{k=-\infty}^{\infty} r_x(k) \cdot r_y(k+\tau) \qquad (1.1)$$

with $r_x = y_1$ and $r_y = y_2$.

For stochastic processes the expectation value E{} is a statistical indicator and equation 1.1 can be described as:

$$r_{xy}(k) = E\left\{x_k{}^* \cdot y(k+\tau)\right\}$$

$$r_{xy}(k) = E\left\{x^*(k) \cdot \sum_{i=-\infty}^{\infty} h(i) \cdot x(k-i+\tau)\right\} \quad (1.2)$$

$$\underline{\underline{r_{xy}(k)}} = \sum_{i=-\infty}^{\infty} h(i) \cdot r_{xx}(k-i) = \underline{\underline{h(k) * r_{xx}(k)}}$$

with x^* = conjugate complex value.

After transforming equation 1.2 into the frequency-domain (eq. 1.3a) we have the result of the QSSE method (eq. 1.3b):

$$S_{xx}(e^{j\Omega}) = \sum_{K=-\infty}^{\infty} x(k) \cdot x(k+\tau) \cdot e^{-j\Omega k}$$

$$S_{xy}(e^{j\Omega}) = \sum_{K=-\infty}^{\infty} x(k) \cdot y(k+\tau) \cdot e^{-j\Omega k} \quad (1.3a)$$

$$\underline{\underline{H = \frac{Sxy}{Sxx}}} = \frac{Y_1}{Y_2} \quad (1.3b)$$

The impulse response H from both sensor-components can be solved by dividing the cross spectral density by the power spectral density!

Case Studies

I present different case studies in different environments to prove the method functionality under several conditions. All data come from permanent ocean bottom cable (OBC) installations with a three component MEMS accelerometer and a hydrophone. The horizontal distances between the sensor nodes are 25m/50m and the cable was trenched or dragged into the sediment in ca. 1 meter depth. The water depth was between 30 meter and 75 meter in the offshore environment in consolidated and unconsolidated sediment.
Figure 1 points out the cross-line component of two nodes with a distance of 50 meter. The result is also valid for the inline and the vertical component, respectively. Due to the omni-directional nature of the random noise and the independence from the signal amplitude the method can easily compare sensors with distances up to 50 meter, maybe more.
Both sensors show a similar signal behavior, and the amplitude response ratio is close to 1 with ca. 0 degree phase shift. Only on the higher frequency end (>40Hz) some spikes occur. Those spikes are most likely related to the coupling to the seafloor, because each sensor component seems to have a different coupling quality. But still, the amplitude and phase response are flat lines over the frequencies of interest and can be used to evaluate the sensor response compared to a second sensor.
Figure 2 shows the comparison of two horizontal MEMS components in consolidated sediments to evaluate the sensor coupling to the seafloor. Sensor coupling is more critical for seafloor installations or OBC than land systems because of different coupling conditions. Poor quality of ocean bottom seismic data is mainly caused by different signal responses on the horizontal components. The coupling to the seafloor is well understood and can be simulated by using damped oscillation spring systems to estimate amplitude and phase as a function of frequency (see e.g. Duennebier et al., 1995). But most of the coupling simulations consider only the vertical component. However, for OBC systems the horizontal coupling requires equal sensitivity and frequency response to the particle motion for the inline and crossline measurements.
Figure 2 highlights only the horizontal sensor components, but a comparison of vertical and horizontal components is possible as well because random ambient noise is omni-direct and should be equal on all components.
The data of two horizontal sensor components are used as input for the QSSE method. Except for some spikes at high frequencies the amplitude is close to one and the phase-shift close to zero. That proves a good signal coherency and can be accounted for as a good coupling of the sensor to the seafloor.
Both, figures 1 and 2 present the method results visually, but for a sensor-array with several 1000 sensor-nodes it is nearly impossible to QC all visual plots. Therefore figure 3 provides a more common way to present the results in a color-coded pass-fail diagram. If for example the frequency ranges from 0 to 100 Hz is in the survey focus the method result can separated into two sections and the values of each section are averaged. The threshold-range was set to 0.99 - 1.01 for the amplitude and +/- 1 degree for the phase-shift. Line 2 shows more fail nodes than line 1. This is due to very soft bio-sediment in the simulation data that the nodes fail with the phase-shift.
The green and red rectangulars in figure 3 represents the pass-fail results for amplitude and phase, if one fail the sensor fails. It is also possible to increase the sections and to separate the amplitude and phase in different rectangulars.

Conclusion

The presented method uses incoherent ambient noise as a statistically common input signal. I have proven that the distance between two sensors is not as important for this method as the omni-direction and the frequency band of the ambient noise. The method assumes only that the ambient noise floor is statistically equal and available on all sensors, which is usually the case.
The simulation and the processing with real data have proven the usability of the QSSE method. This method calculates the amplitude-phase-shift difference of all sensors in a sensor-array without knowledge of the exact sensor transfer-function. In addition to conventional approaches it is possible to evaluate the sensor coupling and to estimate sensors behavior, even if the sensor distance is up to several 10 meters and without direct access to the sensors. The robustness of this function is also proven with different types of sensor data and in different environments. The qualitative different behavior is clearly presented in the frequency plot and can easily be used for seismic QC in a pass-fail-diagram. Comparing the QSSE results from different surveys can increase the 4D data accuracy and the sensor performance over time.
The QSSE results can also be used to increase the pre-processed data quality by setting more precise filter settings.

Acknowledgement

I would like to thank Octio Geophysical for the permission to publish this work and to my colleagues who assisted me in the data collection and the discussion during the tests and processing.

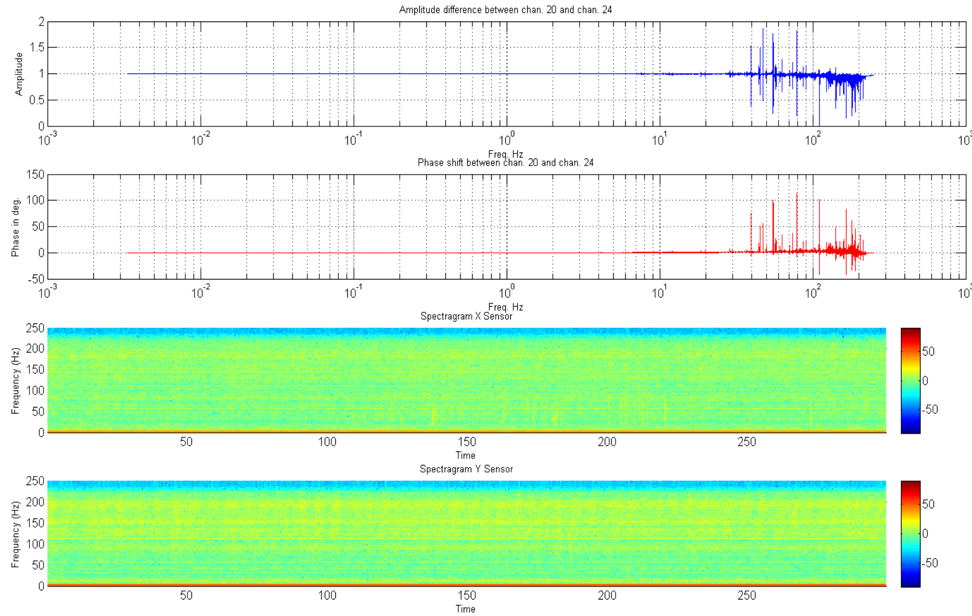

Figure 1: This figure shows the amplitude and phase shift of two MEMS accelerometer cross-line component in the offshore environment in the upper two diagrams. The distance between the two sensor-nodes is 50 meter. The amplitude and phase variations are caused by the different coupling to the seafloor and the small spikes are generated from correlated harmonic signals, not so clearly seen in the frequency spectrum.

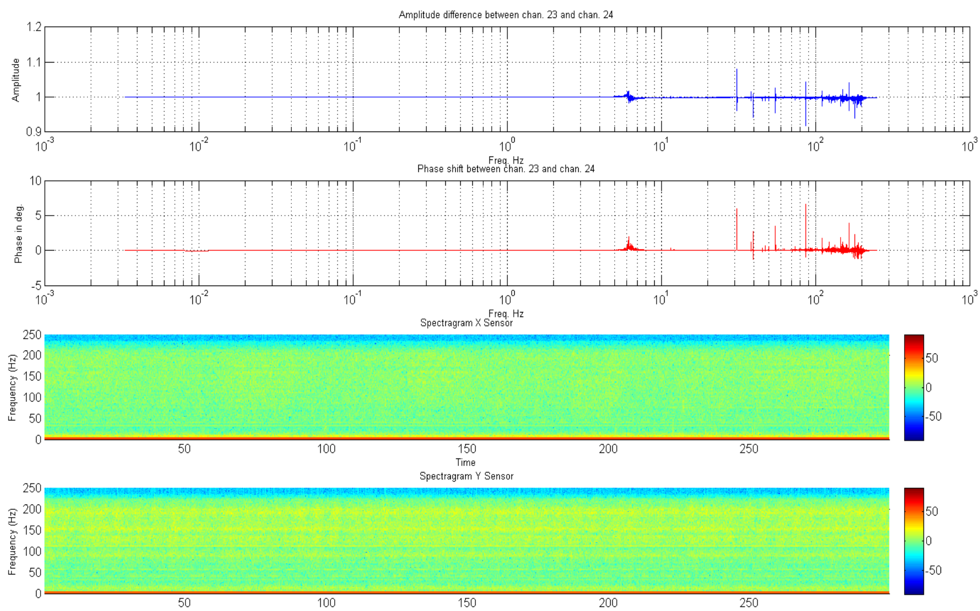

Figure 2: This figure shows the horizontal coupling of a MEMS accelerometer in the offshore environment. The amplitude and phase variations are caused by the different coupling to the seafloor and the small spikes are generated from correlated harmonic signals, not so clearly seen in the frequency spectrum.

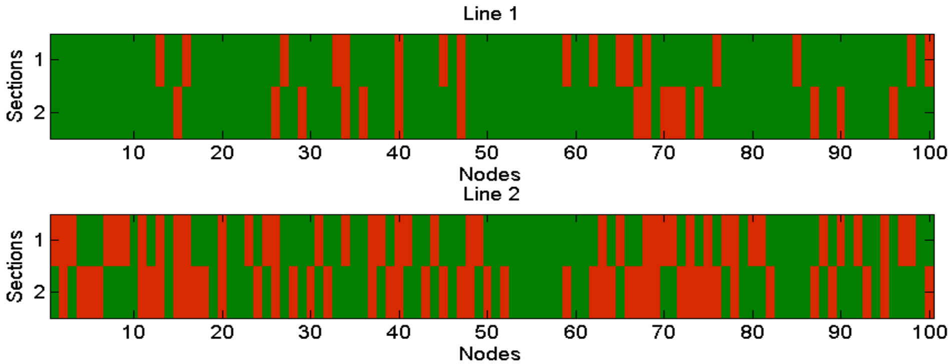

Figure 3: This figure points out the color-coded pass-fail average diagram from two sensor-lines with 100 sensor-nodes each from simulated data. Section 1 represents the frequency-range from 0-100 Hz and the section 2 from 100-500Hz.

ABSTRACT

AGU 2011

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

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Abstract:
The presence of a sensor-node in the seabed produces changes in the local wave field, usually referred to as wave field-distortion due to coupling. In challenging ocean bottom environments it is complicated to enhance coupling of the sensor nodes. But the interaction of Ocean-Bottom-Seismometer (OBS) or Ocean-Bottom-Cables (OBC) with the seabed can be estimated. The system response of the sensor-sediment interaction can be modeled as a mass-spring-dashpot transfer-function with two coupling parameters: resonance frequency and damping-factor. The transfer-function is related to the mass and size of the sensor-housing and the physical properties of the sediment. In order to be able to withstand the hydrostatic pressure at the seafloor, the OBS/OBC is a large and heavy system compared to the soft and water-saturated sediment. This can result in a system resonance which will be within the frequency-band of interest. In order to improve the system coupling it is necessary to estimate the coupling-parameters to shift the coupling resonance to a higher frequency and the damping to critical-damping.

The reliable replication of seismic waves depends on the interaction of the Ocean-Bottom-Cable (OBC) with the seabed, regardless of the direction in which the wave travels. The interaction is called coupling and is typically better on the in-line sensor-component because of the surface enhancing effect of the cable. Inconsistent coupling of multi-component sensor-nodes causes distortions between the horizontal components and this makes the interpretation of converted wave difficult. Horizontal OBC data are often characterized as "ringy" and have different noise levels between inline and crossline. We will show that these characteristics are expected if coupling to the sediment is poor. Coupling and data quality are generally good for the inline component, except for a higher noise floor caused by cable noise. However, the crossline component often exhibits low-frequency resonance. Also, OBCs are susceptible to rotational modes about the cable axis that produce spurious 'S-waves' resonance on the vertical component.

We will present a method to estimate the coupling parameters for both horizontal components independently by using a "feed-back transfer-function" method. The result can be used to optimize the sensor-housing design or to apply an inverse filter in order to extract the coupling transfer-function from the data. The presentation will show that inconsistent coupling of horizontal components can be estimated by using a data-driven approach. The presenting method estimates the two coupling parameter direct from the first arrival wave (first-break) without any affected earth-responses. Neither assumptions like perfect inline coupling have to be made nor will in-situ measurements such as internal shakers be necessary to estimate the coupling parameters.

EXPANDED ABSTRACT

SEG 2012

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

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Summary

The presence of an Ocean Bottom Cable (OBC) in the seabed produces changes in the local wave field due to coupling, usually referred to as wave field distortion. The coupling system response of the sensor sediment interaction can be modeled as a mass spring transfer-function with two coupling parameters: resonance frequency and damping factor. The transfer-function is related to the mass and size of the sensor housing and the physical properties of the sediment. In order to improve the system coupling it is necessary to estimate the coupling parameters to shift the coupling resonance to a higher frequency; and the damping to critical damping. We will show how the coupling parameters (resonance frequency and damping factor) can be used to obtain the sensor housing response by using an “iterative loop” method to estimate the coupling parameters. We will also present two case studies, one in very soft bio sediment in a harbor area and the second in the Gulf of Mexico.

Introduction

The reliable recording of seismic waves depends on the interaction of the OBC sensor housing with the seabed, regardless of the direction in which the wave travels. This interaction is referred to here as coupling. Inconsistent coupling of multi component sensor nodes can cause distortions between all sensor components which makes the interpretation of converted waves difficult (Gaiser, 1996). The horizontal components of OBC data are often characterized as “ringy” and have different noise levels between inline and crossline.

We will demonstrate that these characteristics are expected if coupling to the sediment is poor. The resulting poor quality of ocean bottom seismic data is mainly caused by different signal responses on the two horizontal components; excluding cable and ambient noise. The sensor coupling to the seafloor is well understood by using damped oscillation spring systems to simulate the amplitude and phase as a function of frequency (e.g. Duennebier et al., 1995). Shear wave processing of seismic data involves the analysis of the horizontal particle motion. This analysis requires that the inline, crossline and vertical measurements must be equal in sensitivity and frequency response to the particle motion. It is well known that there is a difference in the frequency response of the horizontal and vertical sensor component (e.g. Gaiser, 2007). These differences in the frequency response in OBC surveys can complicate multi component processing.

We will present a method to estimate the coupling parameters for both horizontal components (inline and crossline) independently by using an “iterative loop transfer-function” method. The result can be used to optimize the sensor housing design or to apply an inverse filter in order to extract the coupling transfer-function response from the data.

Method

Sensor housing coupling to the seafloor can be separated into two different modes: interaction coupling and contact coupling (e.g. Vos et al., 1995). Interaction coupling is usually caused by the sensor housing itself, acting as a disturbing body with respect to the surrounding sediment behavior. If we assume a perfect contact between the sensor housing and the seabed, the presence of the sensor-housing will disturb the wave-field in the sediment. This will have an influence on the resonance frequency and the amplitude and phase-shift of a seismic wave. The measured wave-field is a superposition of the undisturbed field before deploying a sensor and the diffracted field by scattering due to the presence of the sensor-housing. The coupling to the seafloor is well understood by using damped oscillation spring systems to simulate the amplitude and phase as a function of frequency (e.g. Duennebier et al., 1995).

The response model of OBC sediment coupling is based on structural soil interaction and can be described with a transfer-function. The transfer-function source signal is an airgun and we typically use the first-break (direct P-wave) impulse signal arrival to ensure that the signal is not affected by the earth response itself. Only the coupling interaction between the sensor housing and the sediment will affect the source signal. The mechanical interaction between the OBC and the sediment has a second order low-pass response with a specific resonance frequency. The horizontal response includes two coupled modes, translation and rocking (Duennebier and Sutton, 1995). Both horizontal responses interact separately with their own resonance frequency. The interface between sensor housing and seabed changes the wave field and can be modeled as a damped spring mass system. This coupling model is based on structural soil interaction with the sensor housing (e.g. Wolf, 1944; Hover, et al., 1980, Sutton et al., 1981; Duennebier and Sutton, 1995; Dellinger et al., 2001; Gaiser, 2007). The damped spring mass transfer-function can be described in the Laplace domain as:

$$G_{(s)} = K_p \left(1 + 2D\omega_0^{-1}s + \omega_0^{-2}s^2\right)^{-1}, \qquad (1)$$

with $D = d / k$ = damping parameter, $\omega_0 = (k/m)^{1/2}$ = resonance frequency and K_p as maximum amplitude. Equation 1 represents the coupling between the sensor housing and the seafloor and can be completely described with these two parameters D and ω_0. The presented method will focus only on the horizontal sensor components, which makes it a two dimensional problem. We assume that all components are perfectly oriented and that there is no cross-talk between them. The method is also valid for the vertical component, but not discussed here. In fact, the method works independently of direction. The transfer-function is a physical approximation of the seafloor sensor housing interface and describes mathematically the mechanical coupling instead of using least squares methods to fit both horizontal components to the same frequency spectrum. Considering the relationship between the coupling and soil parameters it might be possible to estimate the soil conditions as:

$$K = 2\mu\ (1+\nu)\ A\ l_0^{-1} \qquad (2)$$

$$D = d\ \omega_0\ (2K)^{-1}, \qquad (3)$$

with K=spring constant, D=damping coupling response, μ=shear modulus, ν=Poisson's ratio, A=sensor housing area perpendicular to the force, l_0=sensor housing length, d=damping constant and ω_0=resonance frequency.

The basic idea behind the method is that the hydrophone signal is less affected by coupling than the horizontal sensor components with respect to the first arrival (water P-wave). This signal can be used as a "coupling free" source to estimate the horizontal sensor coupling (e.g. Maaø, 2002). Convolving the hydrophone signal with the coupling transfer-function should give the same signal response as for the horizontal sensor. We consider the (MEMS) accelerometer as a seismic sensor here, but the method is also valid for geophones or seismometers. To compare accelerometer and hydrophone, both datasets have to be in the same domain, so the hydrophone data must therefore be differentiated. Figure 1 shows the workflow for estimating the coupling parameters using an iterative mechanism by comparing the convolved hydrophone signal with the horizontal sensor components. Both signals should reach a specific predefined correlation threshold or the correlation maximum. Otherwise, the coupling values will be changed as long as the criterion is not fulfilled. The method presumes two raw source signals from the same shot and sensor housing: hydrophone and one horizontal component. Using the inline component only shots along the cable (azimuth ≈ 0 degree with respect to the cable) are considered; and for the crossline component only shots orthogonal to the sensor housing (azimuth ≈ 90 degrees) are used. All shots are processed, normalized and averaged to reduce statistical outliers. The hydrophone data convolved with the coupling transfer-function produces a coupled signal response which can be compared directly with the horizontal component. When the coupling parameters are set correctly both signals should have the same shape, and the cross-correlation result should be close to one.

In order to estimate the coupling parameters, a parameter range has to be selected. All parameters have to be tested and the maximum cross-correlation coherency is picked as the best estimation. The method processes the data in the time domain, using Runge-Kutta estimation for the transfer-function, and therefore not much computer power is needed (e.g. Press, 2007).

Measurements

In order to test the method on real data two survey data sets were used. The first set originates from a "coupling test" survey in very soft bio sediment in Husøy harbor, Norway and the second from a test in the Gulf of Mexico.

Husøy harbor test in Norway

This survey was designed to measure coupling and ambient noise under poor coupling conditions. In order to measure these effects an OBC system was installed in a portion of the Husøy harbor area containing very soft bio sediment. A 600m shallow water (~30m) OBC data line was deployed in nearly north-south direction in the Husøy harbor in a u-shaped configuration. The "west"-section was trenched and the "east"-section lying directly on the seafloor. 16 4C sensor stations with 25m spacing were used and 882 shots were recorded with 1ms sample rate. The shooting grid was set to 212.5m by 262.5m and the shot distance was 12.5m by 12.5m. The airgun was a 40 cu-inch G-gun with 2000 psi pressure towed in 1.5 meter water depth. In order to investigate the difference between trenched and untrenched OBC one pair was buried 1 meter into the bio sediment. In addition some of the sensor housing had fins while others had not, in order to investigate the possible rotating, rocking and possible differences in coupling of the sensor housing in or on the seafloor. The processing data window was for all measurements set to 30ms above the first-break.

Figure 2 shows the survey dataset results before and after processing on CRG in the time domain. All hydrophone data are differentiated into the same domain as the horizontal components, but the amplitudes of the hydrophone and horizontal component are quite different; one is in Pa/s^2 and the other in m/s^2. To avoid correlation problems both amplitudes are normalized and possible amplitude offsets are removed. No filter or any other type of pre-processing was applied, i.e. the method works only on the raw data. Both plots show a good signal correlation for the direct arrival. Furthermore, the signal response for all shots was found to be very similar after processing, even for different sensor housing measurements. The "iterative coupled" hydrophone response after processing is closely correlated to the horizontal component due to the correctly estimated coupling parameters. After processing the correlation factor average is 91% which is sufficient to estimate the coupling parameters. All shots used to estimate the coupling parameters are summarized in table 1, where the azimuth is +/- 5degrees for all used shots. The average of the processing represents the coupling parameter estimation.

Gulf of Mexico (GoM) test in the USA

This test was performed to evaluate the crossline vector-fidelity of a 24 km OBC in shallow water (~40m). The cable was deployed on the seafloor and connected with the lead-in cable via buoys. 960 4C sensor stations with 25m spacing were used and 968 shots were recorded with 2ms sample rate and the record length was set to 18sec. The shooting lines were perpendicular to the OBC and the shot distance was 50m. The airgun system was a 4070 Cu-inch array with 2000 psi. The data were processed in the same way as the Husøy harbor test. Due to the survey design only the crossline component was processed. As for the inline component there was recorded an insufficient amount of shots close to the receiver.

All hydrophone data are differentiated into the acceleration domain and all 4C components are normalized as described in the Husøy harbor test. The shape of the raw hydrophone and crossline component is consistent. After processing the correlation factor average is 91% which is sufficient to estimate the coupling parameters to f0 = 466Hz and d = 0.21. The average of the processing represents the coupling parameter estimation.

Conclusion

The method test and field data have shown that inconsistent coupling of horizontal components can be estimated by using an "iterative loop" approach. The presented method estimates the two coupling parameters directly from the first arrival (first-break) without any affected Earth responses from upward traveling PP- and PS-waves. Only the down-going P-wave causes interaction between the sensor housing and the sediment, and was processed by the presented method. Neither assumptions like perfect inline coupling were made, nor were in-situ measurements such as internal shakers necessary to estimate the coupling parameters. The hydrophone channel can be used as a "coupling free" source and convolving it with the coupling transfer-function, as long as the convolved hydrophone signal reaches a maximum correlation to the horizontal component, give consistent coupling parameter estimation. During each "iterative loop" the coupling parameters were changed systematically to increase the correlation.

This Husøy harbor field case of poorly coupled horizontal components shows that at least the coupling of an OBC deployed in water saturated soft bio sediment is less dependent on propagation direction. Both horizontal components have more or less the same resonance frequency, but different damping factors. We think that the high resonance frequency is an indication of acoustic coupling rather than elastic coupling. Sediment measurements with "good" elastic coupling suggest much lower resonance frequencies and higher damping factors.

Acknowledgement

I wish to thank Octio Geophysical for funding and permission to publish this work, and my co-authors and colleagues at Octio and UiB who assisted me in the data collection and the discussion during the tests and processing. Furthermore I wish to thank Jan Petter Fjellanger for inspiring discussions, the Norwegian Research Council for funding this project and Paul Brettwood and Cathy Weber from ION Geophysical for the GoM data.

a) Inline

Azimuth	f_0	d	Corr.
1.59	370	0.4	0.936
0.08	360	0.4	0.968
1.16	410	0.5	0.966
2.66	350	0.4	0.962
4.17	330	0.3	0.947
-0.39	470	0.1	0.94
-0.64	480	0.1	0.959
-1.93	480	0.1	0.923
Average:	**396**	**0.31**	

b) Crossline

Azimuth	f_0	d	Corr.
-94.83	300	0.5	0.92
-93.95	360	0.6	0.96
-93.2	350	0.5	0.92
-92.8	350	0.5	0.92
-92.91	340	0.5	0.94
-93.81	350	0.5	0.9
-94.99	340	0.5	0.9
-95.62	360	0.6	0.9
-94.07	430	0.9	0.93
88.69	370	0.5	0.95
87.92	380	0.5	0.9
Average:	**353**	**0.57**	

Table 1 shows all selected shots from one receiver used to estimate the coupling parameters f_0 and d. The correlation value can be used as a confidence level and shows more than 90% equal signal shape for each shot. In order to avoid statistical outliers the coupling parameters are averaged.

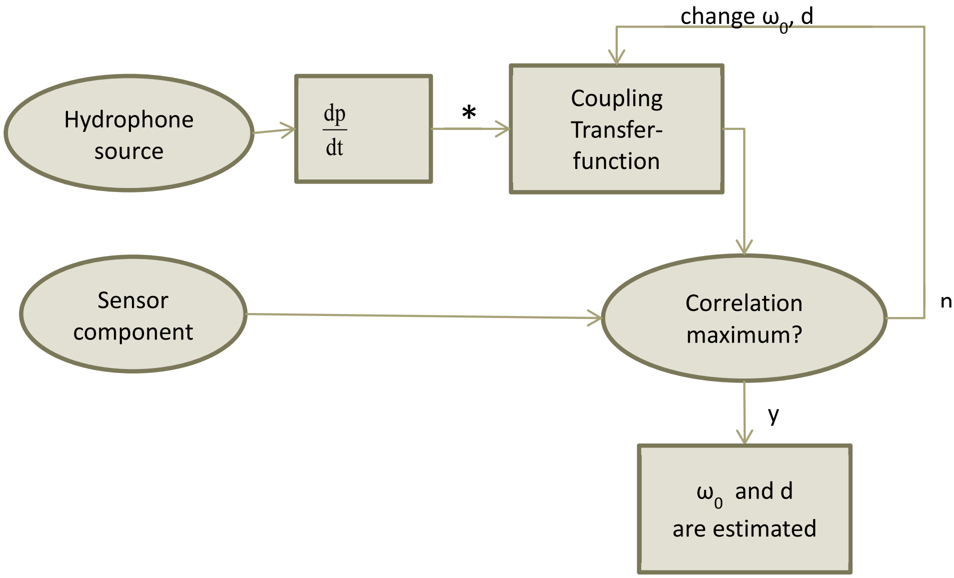
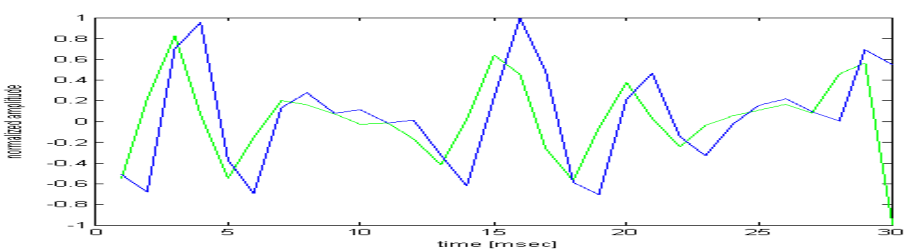


Figure 1 Estimate coupling parameters by using an iterative loop mechanism. The sensor component is an accelerometer and therefore the hydrophone channel has to be derivate to have both data-sets in the same domain. The star between the derivate- and transfer-function block represents convolution. The hydrophone data convolved with the coupling transfer-function and compared with the sensor-component provides a correlation value which should be a maximum. As long as the maximum is not reached the iterative-loop will change the coupling-parameters. At the end the coupling parameters are estimated and the correlation value can be used as a confidence level.

a)



b)

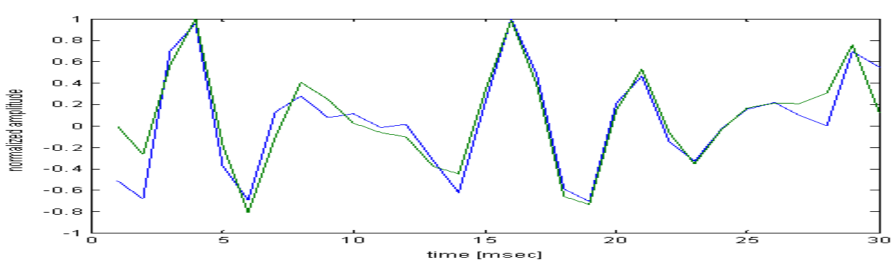


Fig. 2 Hydrophone and horizontal crossline component a) before processing and b) after processing. The blue curve represents the horizontal component. The green curve is the convolved hydrophone response with the best-fit coupling parameters. The x-axis represents the time in msec. and the y-axis the normalized amplitude.

ATTACHED CD

The attached CD contains the Matlab software codes, Excel calculations, Multiphysics models and the conference presentations and poster.

The used data can be applied for from marcus.landschulze@geo.uib.no or leon.lovheim@octio.com.