Directional designature without near-field hydrophone recordings

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Summary

Near-field recordings are commonly used for directional designature to address variations of source signatures with regards to take-off angle and azimuth. We examine two ideas for a case in which near-field recordings are not available. Decomposition of direct waves has the potential for shot-to-shot application, and a global integration of sea-bottom reflection could result in an ensemble of designature operators. Synthetic and field data examples show what can be expected from the application of these methods.

Introduction

For more accurate processing it is necessary to remove the source signature from the recorded seismic reflection data or to shape them to a desired output (i. e. zero phase). In case of 2D marine seismic measurements it is common to use short offset water-bottom reflections to derive a source wavelet. This method usually provides a global solution, hence no shot-to-shot source signal variations are accounted during a survey.

It is now more than 30 years since Ziolkowski et al. (1982) introduced the method of using near-field hydrophone measurements to estimate the source signature, via the so called notional source, of each individual gun in a gun-array. By deriving these notional sources we can also calculate a far-field signature in any direction (take-off angle and azimuth). Since these near-field recordings are available for each shot it is possible to have a shot-by-shot solution to take into account shot-to-shot variations on the source side. Amundsen (1993) has placed a ministreamer underneath the gun-array to record gun signals further away than the 1 m, which is usually the case in Ziolkowski's method.

Some sophisticated techniques use modeling software for calculating far-field source signals. The advanced methods incorporate gun interactions into their equations and different gun types and makes are calibrated to achieve high-fidelity results (for example the Nucleus and the Gundalf packages). In theory, parameter perturbations within the gun-array which are always present during a survey can be taken into account in this approach. In addition, directional effects are addressed easily during the beamforming process.

Oliveira and Brasileiro (2000) suggested a method for source signal estimation based on direct wave arrivals. The technique implies that the individual guns in the gun-array are emitting signals similarly, only their dynamics are different according to their sizes. In this way one can deconvolve the acquisition geometry and the gun-array layout, from the data producing a so called "effective" notional. Then this result can be used for further processing in a designature process.

In this paper we investigate a few methods that could be suitable for directional designature in the absence of near-field hydrophone measurements. One is the use of water-bottom reflections, where take-off angle and azimuth bins are established and for each bin a separate source signature is estimated. Unfilled bins are interpolated or extrapolated by decomposing the available set into notional sources and beamforming them later on. The second option is the utilization of direct wave arrivals to calculate notional sources similarly to the method of near-field hydrophone recordings or the ministreamer method then beamforming produces the necessary source signatures in the required directions.

Utilizing direct waves

In the method developed by Ziolkowski et al. (1982) the number of measurements is equal to the number of unknown notional source signatures. If our measurements are recorded by the normal towed streamers rather than by the closely placed hydrophones then in case of deeper receivers than sources for direct waves the equation in the frequency domain would take the form of

$$H_j(\omega) = \sum_{k=1}^{n} P_k(\omega) \left[\frac{e^{i\omega \frac{r_{kj}}{v}}}{r_{kj}} + R \frac{e^{i\omega \frac{r_{kj}^R}{v}}}{r_{kj}^R} \right]. \qquad (1)$$

This approach is very similar to the ministreamer technique applied by Amundsen (1993), but his approach involves a separate streamer towed in a distance below the source array.

In expression (1) we have omitted the effect of the receiver array. We consider it short, compared to the wavelength in question and they have equal sensitivity. $H_j(\omega)$ is the recorded signal at the j^{th} receiver, $P_k(\omega)$ is the notional

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source signature of the k^{th} gun in the array at circular frequency ω. R is the reflectivity of the water-air interface. r_{kj} is the distance between the k^{th} gun and the j^{th} receiver, while r^R_{kj} is the distance between the k^{th} mirror source to the j^{th} receiver, v is the speed of sound in water and $i^2=-1$. Finally n is the number of individual guns in the array.

In the real world we have a few tens of individual guns in an array and a few hundred or even thousands of recordings of the same shot at different distances. We can form H and P vectors for each frequency and also a matrix X with the elements in the square brackets of equation (1) and write an equation as

$$H = XP \tag{2}$$

Since equation (2) is an over-determined system, one can use an ordinary least-square solution to it. For the sake of simplicity, we neglect the time variance of distances, due to receiver movements.

$$P = (X^T X)^{-1} X^T H \tag{3}$$

In equation (3) T denotes a complex conjugate transpose operation. With this solution we can attempt to recover notional sources for each shot, hence shot-to-shot directional designature filters can be designed by the help of beamformed far-field signatures.

Unfortunately, in real measurements a lot of parameters are not exactly known. We can expect position changes of the guns in the array (Ni et al., 2012) or the reflectivity value, which is usually considered as R= -1, to have a different quantity. Also, the water velocity has a variation. If we have enough redundancy in the number of measurements and there is no frequency variation considered, some of these parameters can be left as unknowns in the equations and we can solve for them simultaneously.

Utilizing sea-bottom reflections

The common technique for source signal estimation is using flattened sea-bottom reflections of short-offset traces that are stacked together. If the water-depth variation allows, and the geology just below the sea-bottom is changing enough, one can expect that the resulting wavelet is a good representation of the source wavelet for the whole survey. With this method usually a near vertical take-off angle source signature is derived. If there is a wide-azimuth survey with significant variation of the water depth one can attempt to build a set of source wavelets based on stacking of water-bottom reflections for separate take-off angle and source-receiver azimuth bins. These source wavelets are the basis for the directional filters that we apply to the reflection data.

Obviously, this set will have missing signatures for certain bins due to poor coverage or nonexistent water-bottom reflection data. To interpolate or extrapolate those necessary missing far-field signatures at the right azimuth and take-off angle we can attempt to decompose the estimated source signatures into their notional similarly to the method described for direct waves. There are some differences due to the different geometry setup. We have to include more terms for the water-air interface to account for the proper ghost effects (I, II, III and IV are used to index the different paths). In addition, because of the flattening and stacking of events at different distances we have to introduce an additional summation over the shots used in the process, where m denotes the number of shots involved and l is used to index the shot itself. The flattening relocates the events to a reference time. This will bring in a reference distance, termed as r_{lj}, into the equation. This is practically the distance traveled by the waves from the gun-array center of gravity to the receiver while reflecting from the water bottom.

$$H_j^R(\omega) = \sum_{l=1}^{m}\sum_{k=1}^{n} P_k(\omega) \begin{bmatrix} \dfrac{e^{i\omega\frac{r_{kj}^{I}-r_{lj}}{v}}}{r_{kj}^{I}} + R\dfrac{e^{i\omega\frac{r_{kj}^{II}-r_{lj}}{v}}}{r_{kj}^{II}} + \\ R\dfrac{e^{i\omega\frac{r_{kj}^{III}-r_{lj}}{v}}}{r_{kj}^{III}} + R^2\dfrac{e^{i\omega\frac{r_{kj}^{IV}-r_{lj}}{v}}}{r_{kj}^{IV}} \end{bmatrix} \tag{4}$$

The H^R vector elements are the products of the stacking process and contain all the different water-bottom stack results for each azimuth and take-off angle bin.

In case we ignore the slight differences of take-off angles within the gun-array for one particular shot-receiver pair we can simplify our equation (not given here), and we end up with a version where only the reference take-off angle and the azimuth matter on top of the gun-array layout. There is no need to involve the actual water-bottom geometry. From this point, we can set up the matrix equations again as in (2) and (3) and have a solution. At the end of the day from the solutions, namely the notional source signatures, we can recreate the source signatures at different azimuths and take-off angles for the missing bins.

Examples

We have tested the proposed methods in a specific survey context. The Declaration project is around 6000 km^2 marine seismic reflection acquisition where a staggered fleet layout is employed with two ships towing 10 cables

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each and there are 3 additional gun boats on top of the two gun-arrays on the two streamer boats (Figure 1). The water depth varies from a few hundred to almost 2000 m. The actual gun-arrays (five identical arrangements) include 34 active individual guns.

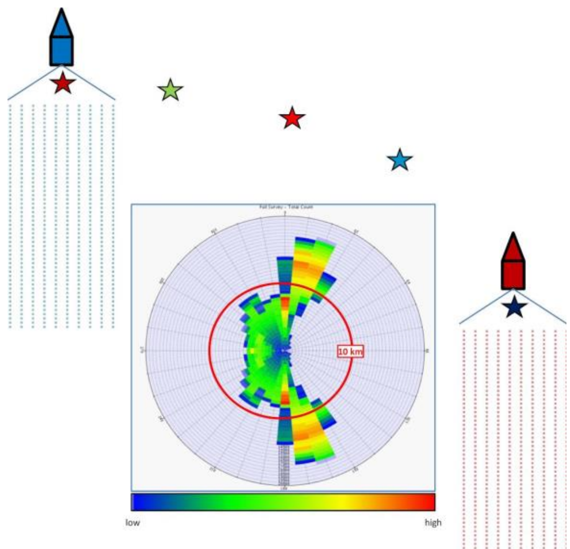

Figure 1: Staggered acquisition geometry with two steamer boats and 5 gun-arrays (highlighted by asterisks). In the middle of the sketch the azimuth and offset distribution of the survey is shown.

First, we investigated how the direct-arrival decomposition works with the specific geometry of the survey at hand. We chose a certain set of shot and receiver combinations and calculated synthetic direct-wave arrivals for a specific shot for each receiver based on notional sources estimated by numerical modeling using a commercial software package. We then input these measurements into the least squares method to get back the original notional source signatures. As can be seen in Figure 2, the solution is satisfactory. We have also investigated the sensitivity of the solution to different parameter errors and found that the way we set up the model, the actual geometry of the survey and the way we solve it make it hard to get reasonable results for our survey specific real life problem. The shot-to-shot directional source signal estimation was not achieved to our satisfaction. The global solution where more redundancy is available and shot-to-shot variations are ignored was still possible, but not discussed here.

Now we turn our attention to the second method, where the water-bottom reflections are utilized for source signature estimation at different take-off angles and azimuths. The aim is now a global estimate, no shot-to-shot solution is available. We have flattened the water-bottom reflection event on every trace and assigned a take-off angle and an azimuth to them. According to these values, the gathers were stacked and a set of source signatures are produced for each bin. If missing bins need to be filled in, the method of decomposition and beamforming described before based on water-bottom reflections can be applied.

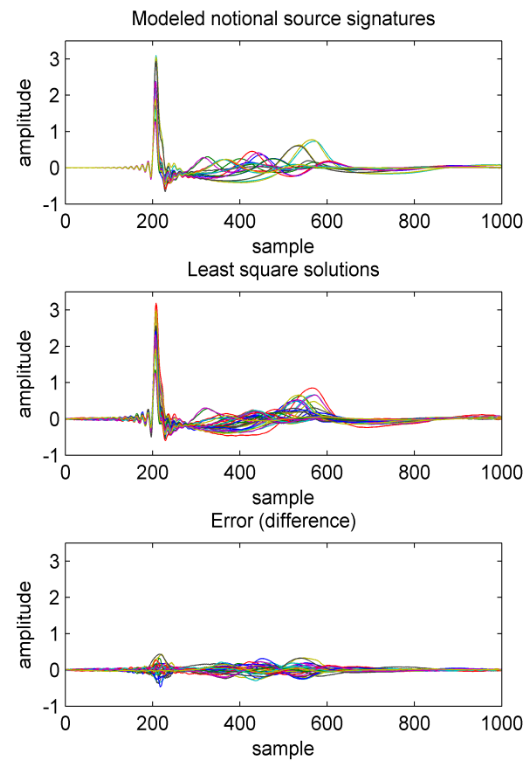

Figure 2: Notional source signatures used for modeling direct wave arrivals (top). Deirved signatures by the least square solution (middle). Difference between the original components and the solutions (bottom).

These results are already suitable for designing directional filtering operators. In our case, we matched these wavelets to spikes to create match filters as the desired zero-phasing filters. For the application of directional designature operators it is common to use the tau-*p* domain to separate the arrivals at different take-off angles. To simplify our approach but still able to use the appropriate filters at different azimuths without mixing traces by tau-*p* we used a technique published by Lacombe et al. (2008). This method divides the traces into overlapping windows and assuming a flat reflector one can calculate the take-off angle applicable to that trace section based on the velocity and layout geometry. Since the azimuth of the source-receiver pair is known for that particular trace, too, there is nothing more to do than to pick the right operator from the appropriate bin of the filter bank and to apply. In Figure 3 a

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shot record can be seen without filtering (a), with filtering, but only the vertical direction is used for every trace (b) and the directional filtering based on the estimated directional source wavelets (c).

Conclusions

Without near-field or other dedicated measurements directional source signature estimation could rely on other sources of information such as direct wave arrivals and water-bottom reflections. Directional waves have the potential to provide shot-to-shot solutions to use for directional designature operator calculations. Water-bottom reflections could result in a global solution. The field data example shown, highlights the applicability of this latter technique where a better filtering was achieved with the target oriented (azimuth and take-off angle dependent) operators compared to a single uniform filter.

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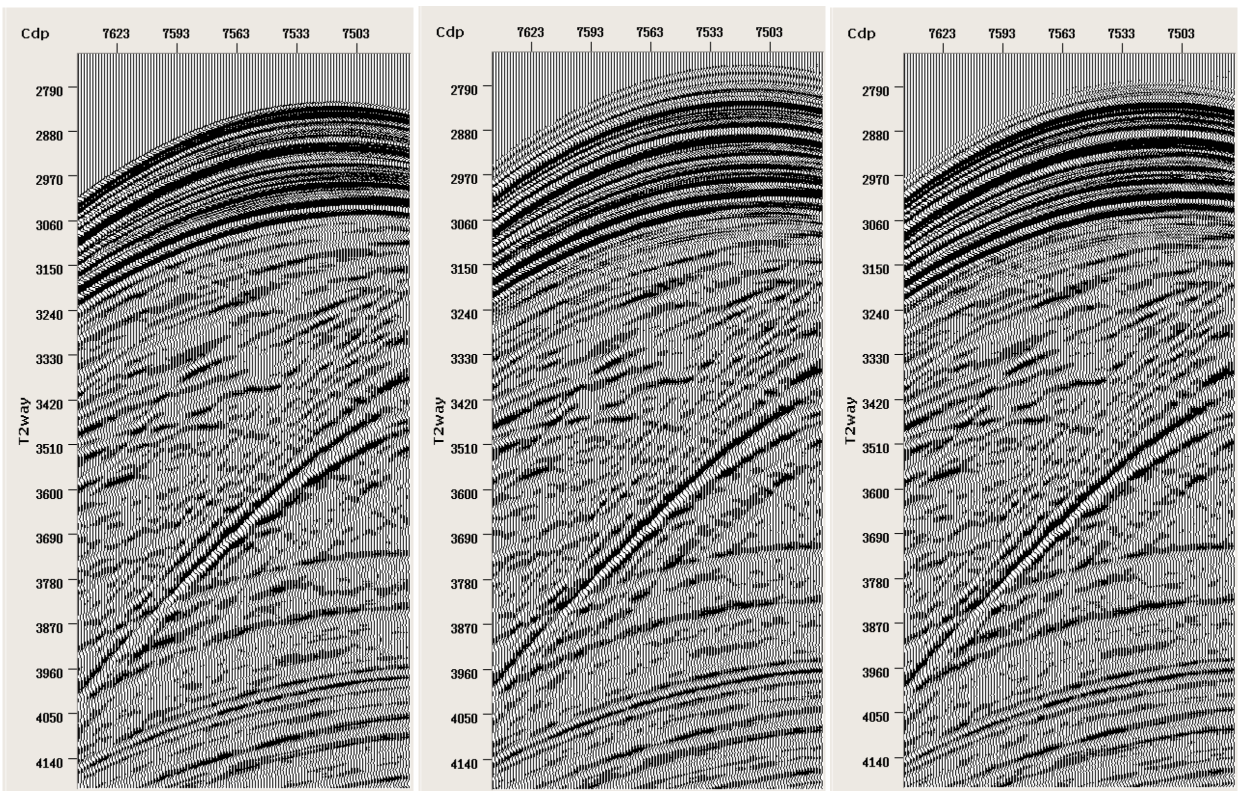

a) b) c)

Figure 3: Part of a record without filtering (a), filtering only with a single filter which is the zero azimuth vertical take-off angle filter (b) and employing the full set of directional filters (c). The main difference is at the earlier times as it was expected.

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EDITED REFERENCES

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