A practical approach to OBC summation and geophone calibration in areas of shallow water and hard seafloor.

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Abstract

A methodology for processing two-component (2C) ocean bottom cable (OBC) seismic data based on the principle of cross-ghosting (Soubaras, 1996) is applicable to some of the most difficult field situations where water depths are in the 20m to 60m range and where there may be a hard variable seafloor giving rise to strong guided waves and geophone coupling "resonances". Effective summation of hydrophone(H) and geophone(G) components depends on geophone calibration to compensate for this seafloor coupling. The methodology breaks naturally into three steps: data analysis and pre-filtering of common receiver records; LS estimation of calibration filters from pre-filtered data; and finally summation. Pre-filtering to attenuate guided and other horizontally propagating waves is a critical step because such waves "in-fill" the ghost notches especially on the geophone records and reduce the effectiveness of cross-ghosting. The analysis of common receiver records is also critical in order that the best data window can be found which contains primarily reflected P-waves.

Introduction

OBC summation methods fall into different categories based on the number of components recorded (2C versus 4C), the water depths of operation, the level of noise, the expected severity of geophone coupling and whether the goal is to eliminate receiver-side ghosts only, or both receiver side-ghosts and water-column reverberations. The source-side ghost is lumped in with the source wavelet. Here we restrict attention to 2C recording of P-waves deemed to be near-normal incidence. In this case it can be shown that the receiver ghost and receiver–side water-column reverberations will cancel on H + s.G records where the scalar s depends on relative hydrophone and geophone sensitivity and seafloor reflectivity (Barr & Sanders, 1989). This is a scalar sum with no 90 degree phase-advance applied to the geophone component as there would be for conventional acquisition in cases where both hydrophones and geophones are deployed immediately below (or close to) the surface.

The main problems with this method are that it requires an estimate of the seafloor reflectivity and ignores the influence of the source-side reverberations which become significant in hard seafloor areas. There is no scalar which will cancel both source and receiver reverberations in the water column. An alternative and more robust approach is to aim to remove the receiver ghost only and leave the water column reverberations to be removed by conventional processing . Without the receiver ghost conventional predictive deconvolution will remove the water-column reverberations under ideal conditions.

During the mid-90s a number of authors recognised that summing 2C OBC data (without resorting to separate calibration surveys) was a non-trivial problem (Ball et al., 1996; Soubaras, 1996). The geophones are affected by seafloor coupling (Gaiser, 1998) and noise from horizontally propagating waves hugging the seafloor makes it difficult to find a representative window where near-normal incidence P-wave reflections predominate. Horizontally propagating waves (for example guided waves, Stonely waves, critical refractions) all can have a serious effect on geophone calibration in that they "in-fill" the ghost notches especially on the geophone component. The problem this poses even for a simple scalar estimation was reported by Dragoset et al., in 1994. The situation for estimating de-coupling filters is even worse and some authors suggested using the critically refracted waves themselves for deriving suitable geophone calibration filters (Melbo, et al., 2002.)

Most formulations of OBC summation reported in the literature are based on a wavefield separation into up-going and down-going waves. Although the boundary conditions at the seafloor (continuity of stress and displacement) force the pressure and vertical velocity to be the same immediately above and below the seafloor this is not true of the up-going and down-going waves. Methods which remove the receiver-side ghost only (Soubaras 1996), effectively compute the up-going wavefield just above the seafloor. Methods which also attempt to eliminate water-column reverberations effectively compute the up-going wavefield just below the seafloor (Barr & Sanders, 1989; Dragoset & Barr, 1992; Olsen, et al., 1999; Ball & Corrigan, 1996). These latter methods do not include the elimination of multiples such as peg-legs with one leg in the water-column or source-side reverberations because such multiples are treated as upward propagating even though they include a downward propagating leg. As recognised by Barr and Sanders (1989) it is sometimes possible to ignore the source side reverberations but not in areas where there is a hard seafloor. Because the impedance of the seafloor sediments is not known these later methods require an estimate of the reflection coefficient of the seafloor. As Ball and Corrigan (1996) point out this may be easier said than done when either component (and especially the geophone) is corrupted by noise. They provide an option in their method to estimate receiver-side ghosts only.

Method

The method adopted in this paper referred, to as ‘Geo_calib’, is based on the cross-ghosting principle outlined by Soubaras (1996) and as such attempts to estimate the up-going wave just above the seafloor. It allows conventional processing and analysis to be easily incorporated for addressing the problems outlined above. Figure 1 is a flow chart showing how the summation and geophone calibration steps fit together in the processing. It can be seen from this chart how direct wave (horizontally propagating) noise may in-fill the ghost notches and why pre-filtering is critical for estimating geophone calibration filters. By choosing to attempt the lesser goal of ghost cancellation only, one ends up with a more practical and robust method. This is particularly true in areas where there are strong guided waves (eg. where the seafloor consists of layers of high velocity limestone) and where the water is relatively shallow. It can then be unrealistic to attempt to estimate both coupling filters and seafloor reflection coefficient with confidence. Furthermore, in relatively shallow water areas, conventional predictive deconvolution will work well on the short-period water-column reverberations and is a much safer option than the subtraction approach implied by a summation method based on the up-coming wave immediately below the seafloor.

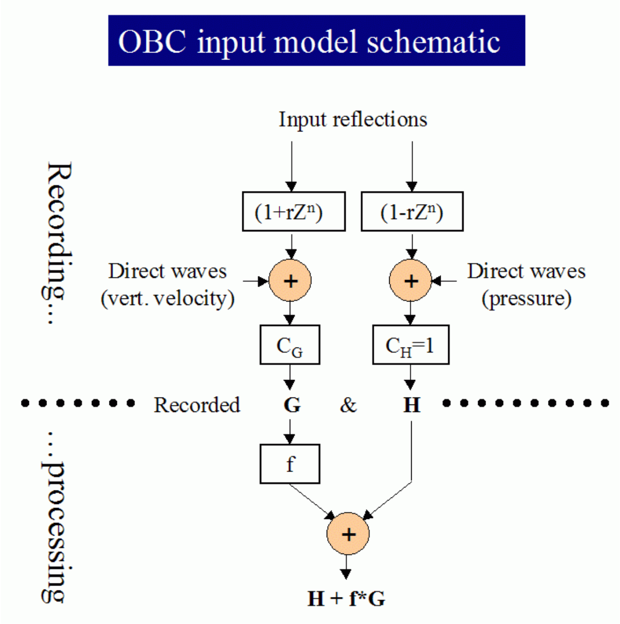

Figure 1. OBC input model flowchart showing ghost responses for P-wave reflections, direct wave superposition and the geophone coupling (recording stage) and the geophone inverse coupling filter, f, needed for summation.

The essential problem of OBC summation is shown in Figure 1 where the ghost filters with delay n samples act on the P-wave reflections and superposition of direct waves follows. For simplicity, we write the ghost delay time as n samples and ignore the issue of interpolation. The sea surface reflection coefficient is shown as r. We assume no coupling effect on the hydrophone ($C_H(z)=1$) but a coupling effect represented by $C_G(z)$ on the geophone which must be estimated. Normally, the hydrophone and geophone transfer functions would already be matched according to the manufacturer’s published data. Often hydrophones used for OBC have responses which match the geophone by design. The recorded components H and G are summed in processing to produce H+f*G where the calibration filter f approximates the inverse of C_G (see Figure 1).

The processing of 2C OBC data must address the problem of direct waves as is indicated in Figure 2. Common receiver point (CRP) noise suppression filters are applied to both the H and G components prior to cross-ghosting. The cross ghosting filters require estimates of the water depth (m samples, say) and the surface reflection coefficient, r. The water depth is estimated independently from survey data. The Geo_calib design window W is selected to choose P-wave reflections which are deemed to be near-normal incidence and to have a start-time greater than the source duration. It is well recognised that especially in shallow water choosing this window is critical (see for example Melbo et al., 2002).

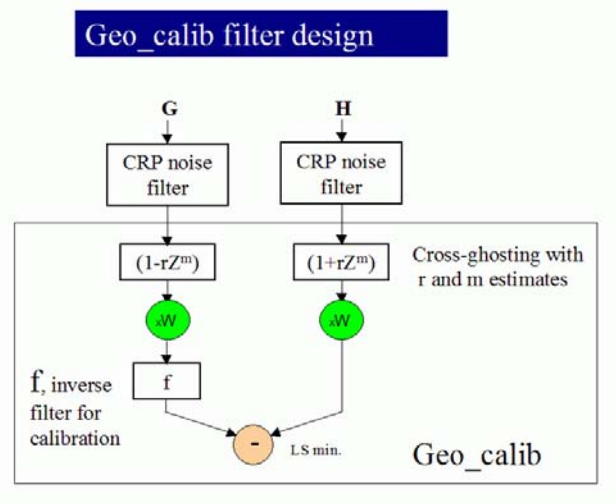

Figure 2. OBC analysis flowchart showing recorded H & G components, common receiver point (CRP) noise filters, cross-ghosting filters and time-offset windowing (W) for LS calibration filter design.

To improve our trace selection within this window, we apply an admissibility criterion aimed at producing a better estimate of f for each CRP gather. One possible approach is to use a threshold of correlation between the H and G components after the application of cross-ghosting. This tends to discard shots within the CRP gather which contribute low signal-to-noise traces. For example, where a high level of residual direct wave noise is present on the G component but not on the H component.

In most modern OBC surveys, receiver fold is high (circa. 1000) because the cost of deploying receivers is relatively high. This high fold allows one to use the admissibility criterion to analyse data quality across many receivers in terms of shot-receiver offset and/or shot-receiver azimuth. The results may not only help to refine the design window W, but can have implications for survey design as well.

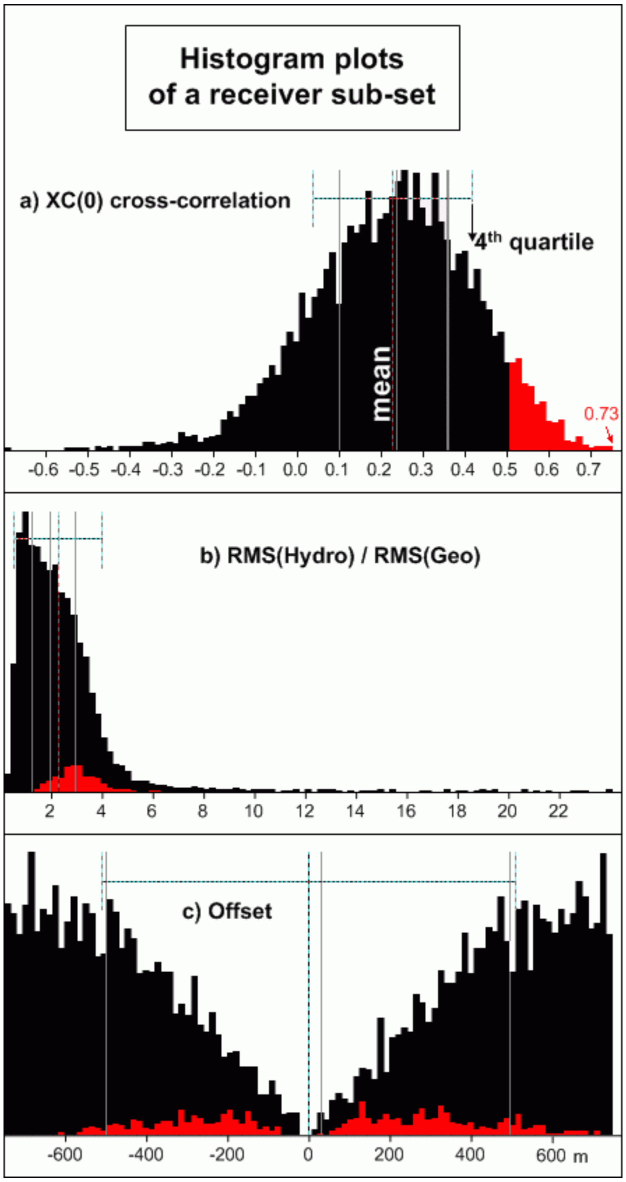

Figure 3: Histogram plots of traces from a receiver sub-set for attributes (a) XC(0) computed on H,G pairs, (b) the ratio of RMS amplitudes H to G and (c) the source-receiver offset. The H, G pairs have pre-filtering and cross-ghosting applied and are limited to the Geo_calib design window, W. In red is the sub-set of traces with a normalised cross-correlation higher than 0.5.

An example of thresholding using the zero-lag normalised cross-correlation (XC(0)) is shown in Figure 3. These histograms are computed for a test set of receivers taken from a prospect in N.E. Brazil where the seafloor is hard and water depths are in the 30m to 50m range. Figure 3(a) shows that the 4th quartile for the XC(0) attribute occurs at a value of 0.42. Setting a threshold of XC(0) > 0.5 will leave enough traces in most CRPs to design a filter f by least squares (red area in the figure). The percentage of traces shown in red in Figure 3(a) can also be interpreted as an indication of data quality for this test set of CRPs. Data quality in this context relates to the potential of summation to cancel receiver ghosts.

Figure 3(b) shows how one might estimate a global scalar (In this case about 3) to give an estimate of average gain needed to match the geophones into the hydrophones. However, the distribution of RMS amplitude ratios shows how much effect coupling of the geophones may be having for these data.

Figure 3(c) shows how the XC(0) admissibility can also be used to analyse the signal-to-noise ratio based on shot receiver offsets within the gather. The presence of strong guided waves on the G component would tend to reduce XC(0). This information can be used to refine the design window for Geo_calib. For the example shown, the design window might be restricted to an offset range of 100m to 600m.

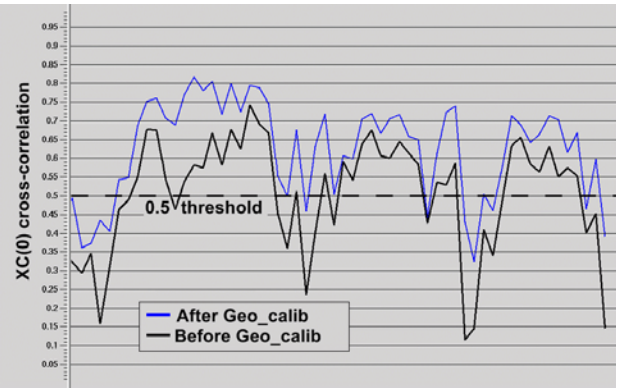

Figure 4: The zero-lag cross-correlation XC(0) computed on a single CRP gather taken from the sub-set used in Figure 3. The black curve shows values before the calibration filter f is applied to the geophones and the blue curve is after. A single f is computed for each trace in the gather.

If we now consider a single receiver taken from the subset shown in Figure 3, we can calibrate the geophone for every cross-ghosted trace pair. Computing an f for each trace in the gather is for analysis purposes only. The final result must be to find a single filter for each receiver.

This example receiver is from a relatively low noise area of the prospect. Figure 4 shows a plot of XC(0) before (black curve) and after calibration (blue curve) for all traces in the gather. These values are computed on the Geo_calib design window. Traces corresponding to some shots have post calibration XC(0) values as high as 0.8. Others have values as low as 0.15. Clearly there is potential benefit in designing a calibration filter, f, for this receiver, using traces with XC higher than some threshold (0.5 in this example). A single least-squares filter, f, is then computed for the receiver using only these traces.

Results - example receiver gather

It is often quite difficult to evaluate the post-summation H+f*G traces especially on noisy data. As reverberations are still present, it is just the effective receiver ghost cancellation that must be measured. An alternative approach is to evaluate results pre-summation using cross-ghosted H and f*G pairs. These can be plotted as an interlaced display on selected common receiver gathers. In order to track the main events, it sometimes helps to apply NMO to the gather for display purposes only.

Figure 5 shows such an interlaced display of the example receiver gather discussed above. Trace pairs are plotted in shot order and three shot lines are shown. This helps to maintain event continuity as nearby traces tend to correspond to similar ray paths. In other words, trace pairs from very different azimuth's are not juxtaposed except when one shot line changes to another.

The display shows a number of reflection events where the phase and amplitude of the event is consistent across the H, G pairs. Note that events E2 (trough) and E3 (peak) are evident across the 3 shot lines. The offsets displayed are restricted to the range 100m to 350m. This indicates that receiver ghosts will cancel on the summed H + f*G traces.

Summary

A methodology for processing 2C OBC data based on cross-ghosting can be applied to areas where water depths are relatively shallow and the seafloor is hard. Successful cancellation of receiver ghosts does not require an estimate of the seafloor reflection coefficient but it does require good estimates of geophone calibration filters. The fidelity of these filters requires an estimate of the water depth, pre-filtering of direct wave noise and special analysis techniques for selecting a design window W for the filters. These techniques include thresholding for trace selection within the common receiver gathers.

Acknowledgments

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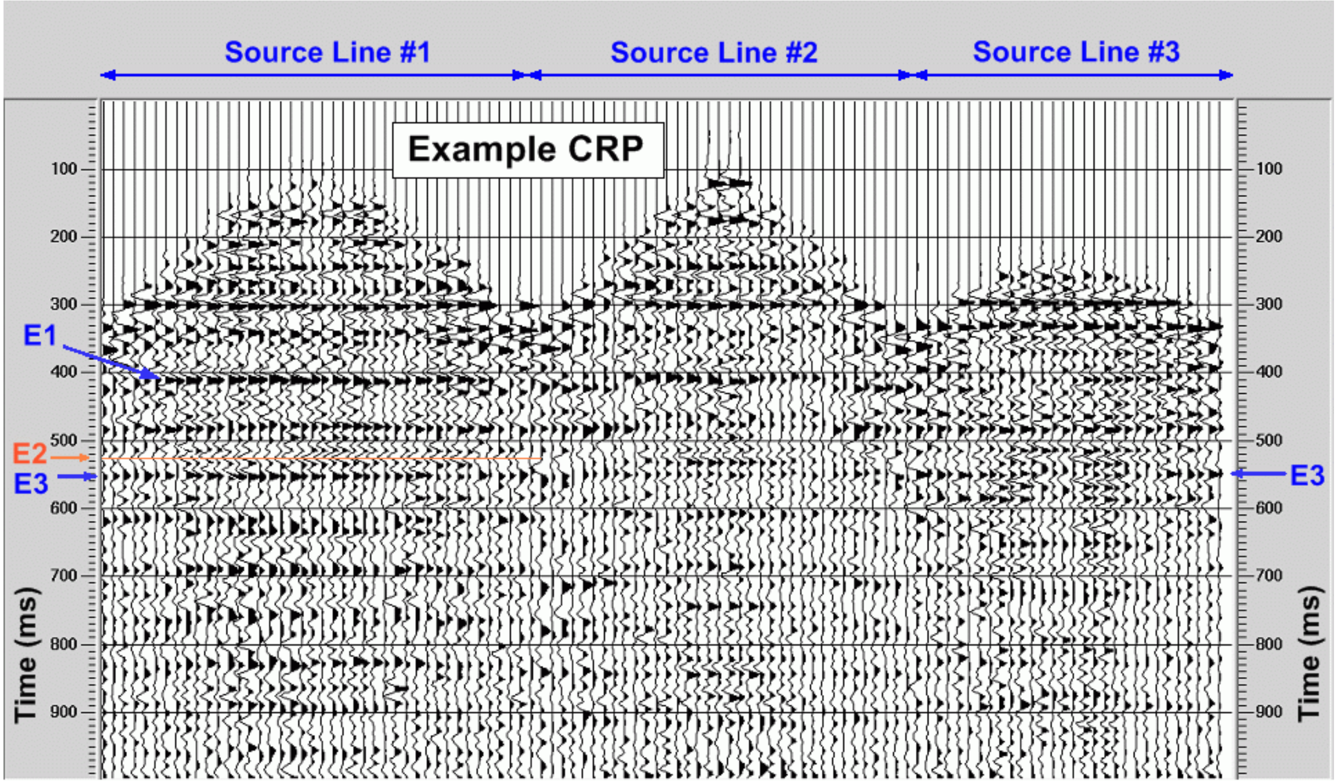

Figure 5: An example common receiver point gather (CRP) with X-ghosted H and G traces interleaved. Each trace originates from one of three shot lines. Offsets are restricted to the range 100m to 350m. Geophones (G) have been calibrated. Three events E1, E2, E3 have been labelled and show that H and G pairs match approximately in both amplitude and phase. This is a requirement for a quality summation in which receiver ghosts are suppressed.