Dual-sensor streamer data: calibration, acquisition QC and attenuation of seismic interferences and other noises

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Summary

Pressure and velocity sensors contained in a towed streamer must be properly calibrated before they can be algebraically combined to separate up- and down-going waves. Statistical techniques developed for ocean-bottom surveys are adapted to account for the marine streamer acquisition geometry. Byproducts of this calibration process provide quality indicators that can be used during acquisition to assess data quality in real-time. Another unique feature of this process is that it isolates external noises, such as seismic interferences. These identified noises can subsequently be surgically removed from the data.

Introduction

Dual-sensor streamer data share many similarities with dual-sensor ocean-bottom cable data (OBC). Consequently, a number of processing techniques developed for OBC can readily be applied to dual-sensor streamer data. However, there are some major differences that make processing of dual-sensor streamer data unique. First, the sensors are constantly moving, which generates significant low frequency noise in the velocity sensors. Second, the geometry is that of a towed streamer acquisition, so each sensor only records a given range of offset and azimuth, and it is impossible to form an OBC-like receiver-gather. Third, the sensors are not at the sea-bottom but close to the sea-surface, which means that the ghost period is different from the peg-leg multiple period.

The first point is critical to the technology because it essentially means that the low frequencies (0-20Hz) of the velocity sensor are overwhelmed by streamer motion noise and that only the hydrophone can be used in that range (Tenghamn et al., 2007). This is a key difference with OBC where the geophones contribute significantly to the low frequency content of the deghosted data. It has also been shown that the proper separation of up- and down-going waves requires accurate calibration between sensors (see for example Backus et al., 2007). Most OBC calibration techniques require a well sampled receiver gather (see for example Ball and Corrigan, 1996; Soubaras, 1996) which is simply not available with streamer data. Finally, some OBC dual-sensor summation techniques take advantage of the fact that receiver ghost and peg-leg multiples have the same period (see for example Barr and Sanders, 1989). Such techniques are inapplicable with dual-sensor streamer data.

In order to match the results obtained with OBC data, new techniques have to be designed specifically for dual-sensor streamer data. In this paper we focus on the calibration issue. We develop a simple and effective process that gives access to calibration filters as well as a number of quality indicators. These attributes can be calculated almost in real-time meaning that they can be used on-board as acquisition QC. Furthermore, this technique can also be used to estimate and remove rig noise and seismic interferences, as well as to generally enhance signal-to-noise ratio.

Dual-sensor summation for wave-field separation

A dual-sensor device made of a hydrophone H and a geophone G placed in a body of water records both up- and down-going waves according to the expression (neglecting noise):

$$H = \left(P^{up} + P^{down}\right)\, h \quad \text{and} \quad G = F\,\left(P^{down} - P^{up}\right)\, g\,, \qquad (1)$$

where P^{up} and P^{down} are the up- and down-going pressure fields, h and g are the impulse responses of the hydrophone and geophone respectively, and F is an operator that can be expressed in the Fourier domain as (Amundsen, 1993):

$$F(\omega, k_x, k_y) = \frac{k_z}{\rho_w \omega}, \quad \text{with} \quad k_z = \sqrt{\left(\frac{\omega}{v_w}\right)^2 - k_x^2 - k_y^2}\,. \qquad (2)$$

In the above formulae k_x, k_y and k_z denote the three components of the angular wavenumber vector; ω is the angular frequency; ρ_w and v_w are the density and acoustic velocity of water.

Retrieving P^{up} and P^{down} from the two measurements is then just a matter of basic algebra:

$$P^{up}\ h = \frac{1}{2}\left(H - \frac{h}{gF}G\right) \quad \text{and} \quad P^{down}\ h = \frac{1}{2}\left(H + \frac{h}{gF}G\right). \qquad (3)$$

Here the up- and down-going waves keep the impulse response of the hydrophone.

Dual-sensor calibration

Equation (3) shows that the velocity sensor needs to be calibrated before being added to (or subtracted from) the pressure sensor. This calibration must account for the devices impulse responses, water impedance and the angles of incidence. In theory, the instrument responses are known, density and velocity of water can be measured on prospect, and the angles of incidence are calculated from the data themselves. Thus, the calibration can be performed deterministically. In practice however, instrument sensitivity can vary, water impedance may change (with temperature and salinity) and actual instrument coupling can be an issue, especially for OBC. There is therefore the need for a statistical calibration of the two sensors prior to summation. This calibration step is rendered all the more necessary with dual-sensor towed streamers because the missing low frequency geophone data are reconstructed using hydrophone data (Tenghamn et al., 2007). Accurate sensor calibration is critical for this process.

There have been many published examples of statistical dual-sensor calibration techniques, but they are all essentially based on the principle that the total pressure field at the water surface is nil. Consider the following steps: assume the two sensors are properly calibrated, compute the up- and down-going pressure fields according to equation (3), extrapolate these fields to the water surface and sum them. If the sum is zero, the original calibration was correct. If the sum differs from zero, some of our original assumptions were incorrect. The culprit could be either the calibration filters or the extrapolation step (inaccurate sensor location or non-flat sea-surface). Note also that even if all our assumptions are correct, there should always be some residual energy in the sea-surface total pressure field: the direct wave, which does not cancel out in the process (because receivers are generally located below the source), and external noise, such as seismic interferences or rig noise.

The process described above can be seen as a massive inverse problem where we estimate the calibration filters, the sensor locations, the source signature and the sea-surface condition by minimizing the energy of the total pressure field extrapolated at the sea-surface. This complex scheme can actually be greatly simplified in the OBC context. Since sensor location and coupling condition do not change, the data under analysis can be restricted to zero-offset. In this case the calibration filter is 1D (k_x, k_y equal zero in equation (2)) and the extrapolation step reduces to a simple time shift. It then becomes straightforward to estimate the sensor depth and the calibration filter (which includes water impedance, sensor matching and the coupling condition) for each receiver location (Soubaras, 1996).

Dual-sensors in a towed streamer do not benefit from this simplification. Since the receivers only see a fixed and limited offset and azimuth range, the 1D assumption cannot be met. Hence the calibration filters and the extrapolation step must be performed in 3D. Also, since receiver locations change from shot-point to shot-point, coordinates must be estimated for every single shot-point. However, unlike OBC data, the coupling condition is not a major concern. Because the streamer is buoyant, the velocity sensors are actually perfectly coupled to water (identical density). Hence we can safely assume that the calibration filters (including water impedance and sensor matching) vary very slowly in the course of a survey, which gives us the redundancy necessary to solve the inverse problem.

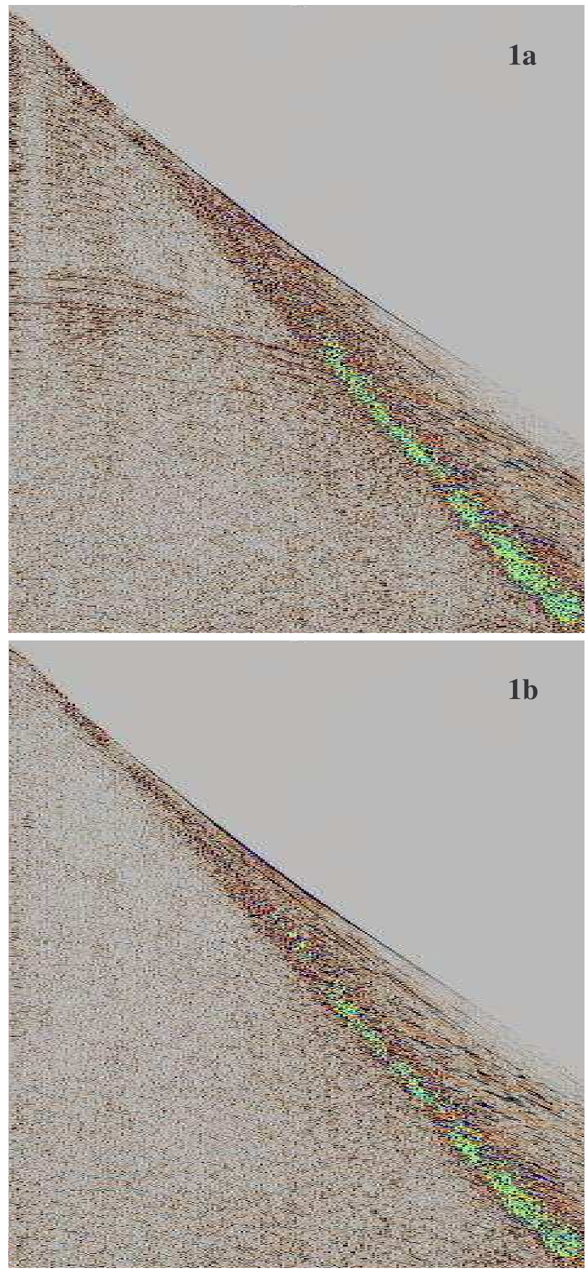

Figure 1: Total pressure field extrapolated at the sea-surface using the incorrect (top) and correct (bottom) sensor depths. Residual energy reduces to the direct wave when the correct depths are used.

Figure 1 illustrates the process using a 2D data example acquired with a variable streamer depth (Söllner et al., 2008). The nominal depth of 15m could not be maintained at the front-end and the streamer dived to 23m. Figure 1a shows the total pressure at the sea-surface using the nominal streamer depth. The large amount of residual energy is evidence that one of our assumptions was wrong (in this case the sensor depth). The energy content is minimized when using the correct depths as all reflections have been eliminated from the residual panel (Figure 1b). The remaining residual energy in Figure 1b is made of the direct wave and wide incidence angle arrivals not properly handled by the process.

Application to acquisition QC

The procedure described above can be applied almost in real time onboard. The resulting calibration filters are displayed to assess if instrument sensitivity drifts with time. The inverted receiver coordinates are compared to the locations derived from acoustic positioning on a shot by shot basis. Figure 2 shows the inverted sensor depth (the x and y coordinates are not calculated in 2D) compared to the depth controller (bird) measurements. The fact that these two independently computed sensor depths are broadly in agreement gives us confidence in the process. Note that the birds are sparsely distributed on the streamer so the depth values are interpolated between the actual measurements. Note also that these measurements are generally averaged over a number of shot points to remove the influence of small wavelength surface waves, while the inverted sensor depths include the wave height. Figure 2 also shows the correlation coefficient between P^{up} and $-P^{down}$ extrapolated at the sea-surface. The good match shows that the inversion was successful. Note the lower correlation values at the depth controller locations due to the amount of noise the birds generate, especially on the velocity sensors.

Noise attenuation

A simple way to improve the signal-to-noise ratio of our calibrated data is to subtract the extrapolated fields at the sea-surface. Since P^{up} and P^{down} are almost identical with opposite polarity, their difference gives a 3dB signal-to-noise ratio improvement of the deghosted data by virtue of the "square-root law." Figure 3 shows a series of shot point gathers and the noise removed following this process. In addition to random noise (especially at the bird locations) the direct wave and a multiple train of wide angle water-bottom refractions are also attenuated.

More promising, however, is the attenuation of external noise such as seismic interferences or rig noise. Figure 4 shows a gather contaminated by the shot from a nearby vessel. Although these interferences appear randomly, they sometimes have the same amplitude and the same moveout as genuine reflections. It is virtually impossible to design a filter that would remove the interference while leaving the reflection data untouched. The interference noise is much weaker on the velocity data because it comes from the side and does not create much vertical motion. The total pressure field extrapolated at the sea-surface allows the best discrimination between reflection signal and interference noise: the signal cancels out and only the noise (and the direct wave) remain. This isolated noise train can then be used to surgically remove the interference in the original gathers.

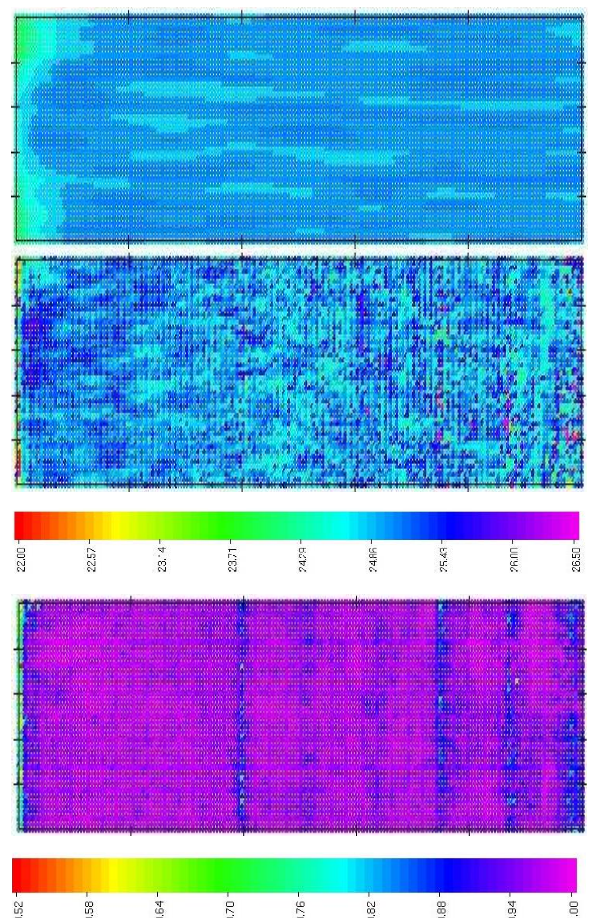

Figure 2: Attributes calculated for a 2D acquisition at a nominal streamer depth of 25m. Only 50 shots (vertical axis) and the first 200 channels (horizontal axis) are displayed. Bird derived sensor depths (top) are in good agreement with the inverted depths (middle). The correlation coefficients of up- and down-going waves are close to –1 (bottom) except at the bird locations.

Conclusions

Although dual-sensor streamer data have some key differences with OBC data, many of the processes derived for OBC can be extended to dual-sensor streamer. In particular, a statistical calibration procedure provides key components for the accurate estimation of up- and down-going waves, as well as a number of QC attributes that can be used onboard the vessel. This procedure also offers the potential of increasing the signal-to-noise ratio of the deghosted data by 3dB. Finally, it can be used to isolate external noise, such as seismic interferences or rig noise, and use this information to surgically remove that noise from the data. This procedure has so far been applied successfully to 2D data but can be readily extended to 3D.

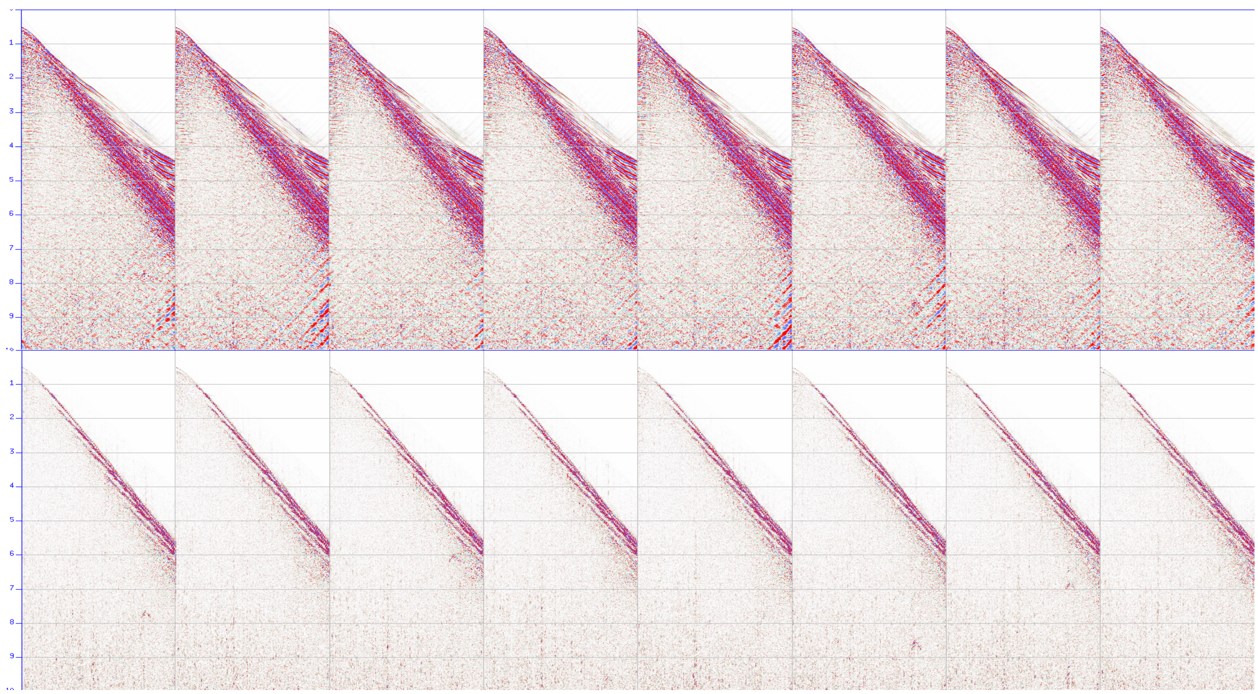

Figure 3: Shot points after combination of up- and down-going energy to remove random noise (top). Noise removed by the process (bottom). In addition to random noise, a wide-angle multiple train of water bottom refractions has also been attenuated.

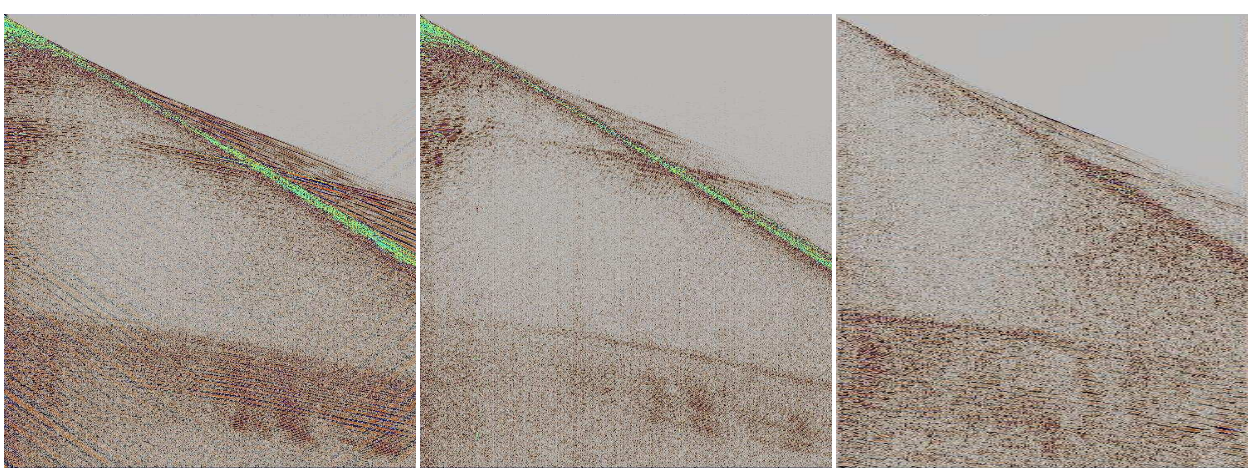

Figure 4: Pressure data (left), velocity data after a 20Hz high pass filter (middle) and total pressure field extrapolated at the sea-surface (right). Reflection data cancel out and only the direct wave and a seismic interference remain.

EDITED REFERENCES

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