Space-frequency domain processing of irregular dual-sensor towed streamer data

Walter Söllner, Anthony Day, Hocine Tabti, PGS.*

Summary

When combining pressure and particle velocity sensor records obtained using a dual-sensor streamer, it is convenient to perform a number of processing steps in the frequency-wavenumber domain. This approach assumes that the recording surface is flat, and if this assumption is violated errors will be introduced. In this paper, we present a space-frequency domain method for processing dual-sensor streamer data that removes the need to make this assumption. The method is illustrated using synthetic and field data examples.

Introduction

One of the principal advantages of acquiring seismic data with a dual-sensor towed streamer is the ability to separate the wavefield into up- and down-going components. The necessary processing steps for achieving this separation are described by Carlson et al. (2007). The up- and down-going pressure fields are obtained by combining the total pressure field record with a scaled version of the vertical particle velocity field record. This scaling factor is the acoustic impedance divided by the cosine of the incidence angle (obliquity factor). The obliquity factor is required because we measure only the vertical component of particle velocity. It is this aspect that makes frequency-wavenumber domain processing attractive as it easily permits individual scaling of each plane wave component. Processing for individual plane wave components is a feature we wish to preserve for variable depth processing.

For the 2-D case with which this paper is concerned (the 3-D extension is formally straightforward), the up- and down-going pressure fields are defined by Carlson et al. (2007) as follows:

$$P^{up}(\omega,k_x)=\frac{1}{2}\left(P(\omega,k_x)-\frac{\rho\omega}{k_z}V_z(\omega,k_x)\right) \quad (1)$$

$$P^{dn}(\omega,k_x)=\frac{1}{2}\left(P(\omega,k_x)+\frac{\rho\omega}{k_z}V_z(\omega,k_x)\right) \quad (2)$$

with $k_z=\sqrt{\left(\frac{\omega}{v_w}\right)^2-k_x^2}$.

In the above formulae P and V_z are the frequency-wavenumber domain representations of the pressure and vertical particle velocity records respectively, k_x and k_z denote the components of the angular wavenumber vector, ω is the angular frequency, and ρ and v_w are the density of water and the acoustic wave propagation velocity in water respectively. Similar expressions can be derived to separate the vertical particle velocity field into up- and down-going components.

After wavefield separation, the up- and down-going wavefields can be extrapolated independently to any observation depth. This procedure is also conveniently formulated in the frequency-wavenumber domain:

$$P^{up}(\omega,k_x\mid z=z_O)=P^{up}(\omega,k_x\mid z=z_R)\exp\left[ik_z(z_O-z_R)\right] \quad (3)$$

$$P^{dn}(\omega,k_x\mid z=z_O)=P^{dn}(\omega,k_x\mid z=z_R)\exp\left[ik_z(z_R-z_O)\right] \quad (4)$$

where z_R is the recording depth and z_O is the desired observation depth.

These frequency-wavenumber domain formulae are applicable to a flat recording surface. However, in practice this requirement may not be fulfilled. In this paper, we first present the results of a synthetic modeling study conducted to assess the sensitivity of the processing steps to irregularities in the recording surface. We go on to describe a generalization of the frequency-wavenumber domain algorithm that allows these irregularities to be handled, which is demonstrated using synthetic data examples. Finally, the procedure is applied to dual-sensor towed streamer data that were acquired with streamer depth variations far outside normally acceptable tolerances.

Sensitivity analysis

A synthetic modeling exercise was conducted in order to measure the effect of an irregular recording surface when processing dual-sensor data using a flat surface assumption. The model comprised a single diffractor located directly beneath the source at a depth of 1000m. The vertical far-field signature for a typical source array was used to generate synthetic data. Data were simulated for a single 2-D dual-sensor streamer at a depth of 15m, which is typical of dual-sensor towed streamer operations. The up-going pressure field at 8m depth was also modelled. This represents a typical acquisition depth for conventional towed streamer operations. Wavefield separation was performed for the dual-sensor streamer data and the up-going pressure field extrapolated from 15m to 8m depth using the frequency-wavenumber domain procedures outlined in equations (1) and (3). Such processing is often performed when dual-sensor data is compared with conventional data acquired in the same area.

To simulate an irregular acquisition surface, a sinusoidal depth variation was introduced to the dual-sensor streamer whilst maintaining a mean depth of 15m. The sinusoid has a wavelength of 1000m and the receiver immediately above the diffractor was at 15m depth. Data were modeled for 0.5m and 1.0m amplitude depth variations. These data were then processed in the same manner as for the flat streamer using an assumed recording depth of 15m.

The up-going pressure field at 8m depth was modeled and compared to the output of processing the synthetic dual-sensor streamer data. The normalized RMS amplitude of the difference between corresponding traces in the two datasets and the time shift between them were calculated. These attributes are shown in Figure 1. This figure shows that the error introduced by the processing sequence is very small when the streamer is flat. For the streamers with a sinusoidally varying depth profile, the errors are similarly small at locations where the streamer depth matches the depth assumed in processing: at channel 241, directly above the diffractor, and 500m away at channel 281. Away from these locations, the magnitude of the error varies in line with the error in assumed depth.

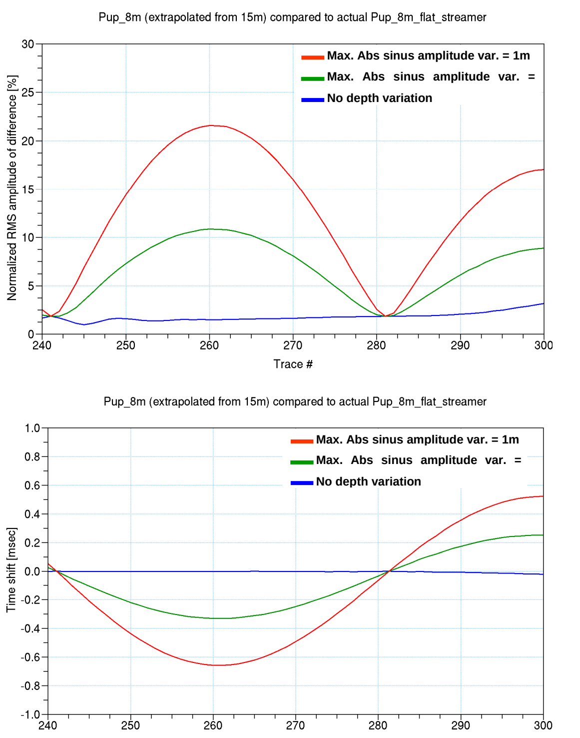

Figure 1: Normalised RMS difference (top) and time shift (bottom) between the up-going pressure field at 8m derived from processing synthetic dual-sensor streamer data and the modeled reference. The trace separation is 12.5m. Channel 241 is directly above the modeled diffractor.

The specifications for towed-streamer surveys typically require the streamer depth to be maintained within +/-1m of the nominal acquisition depth. This synthetic modeling indicates that, at the extremities of this tolerance, significant timing and amplitude errors can occur in the wavefield separation. This result provides the motivation to develop a processing method that allows irregularities in the streamer depth profile to be handled.

Space-frequency domain processing

The principal cause of the errors shown in Figure 1 is the extrapolation step in equation (3), which assumes that both the recording and output surfaces are flat. This introduces a timing discrepancy between the modeled up-going pressure field and that derived from processing the synthetic dual-sensor streamer data at locations where the true depth is at variance with the assumed depth. These discrepancies are reflected in both the time shift and normalized RMS difference attributes. The ability to accurately extrapolate the separated wavefields is an important part of dual-sensor streamer data processing – for example it is required by the surface related multiple suppression technique described by Söllner et al. (2007).

A further complication is that the particle velocity sensor records the component of velocity normal to the streamer in the vertical plane containing the streamer. Hence if the streamer is not horizontal, the sensor does not record the true vertical component of particle velocity. In practice, for the towed-streamer the deviation from the horizontal is very small.

In order to deal with these issues, we perform wavefield separation in the space-frequency domain. The pressure and the normal component of particle velocity are recorded by a receiver cable at depth $z = z_R(x)$ below some horizontal datum. This geometry is depicted in Figure 2. Note that the sea surface may be of arbitrary shape and located between the datum and desired observation levels – it need not coincide with the datum level.

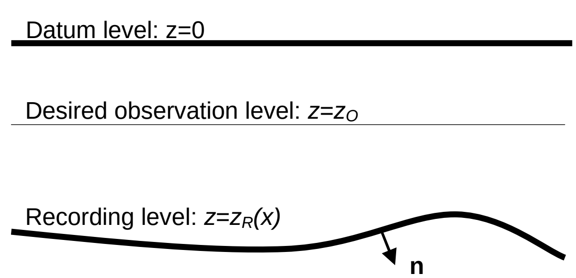

Figure 2: Schematic of acquisition geometry. **n** is the unit vector normal to the recording surface.

Using the field reciprocity theorem, Fokkema and van den Berg (1993) obtain the following expression for the up-going pressure field at the datum level:

$$P^{up}(\omega,k_x \mid z=0) = -\frac{1}{2ik_z}\int \left\{ \begin{array}{l} i\omega\rho\cdot v_n(\omega,x \mid z=z_R(x))\exp\left[ik_x x - ik_z z_R(x)\right]+ \\ p(\omega,x \mid z=z_R(x))\mathbf{n}\bullet\nabla\exp\left[ik_x x - ik_z z_R(x)\right] \end{array} \right\} dx \qquad (5)$$

where p and v_n are the frequency domain representations of the pressure and normal particle velocity respectively at the receiver cable depth. For a horizontal streamer the integral can be recognized as a spatial Fourier transform and the expression is equivalent to a combination of equations (1) and (3).

Since the result from equation (5) is the up-going pressure field at a horizontal datum, extrapolation to any other desired observation level can be achieved using equation (3). Furthermore, the transformation back to the space-time domain can be performed using a fast Fourier transform. Hence the extra computational expense involved in a practical implementation of this algorithm compared to the horizontal streamer case is approximately equivalent to the difference between performing the forward spatial Fourier transform by means of a direct versus fast Fourier transform algorithm.

Finally, note that a similar expression can be derived for the down-going pressure field. The up- and down-going vertical particle velocity fields can also be obtained by appropriate scaling.

Data example

During acquisition of dual-sensor towed streamer data in the North Sea, a line was acquired for which the front part of the streamer was much deeper than the streamer depth specifications permit. The nominal streamer depth was 15m, but channel 1 was at 22.5m depth, with the depth discrepancy gradually reducing to zero around channel 70 as depicted in Figure 3. Normally, such a line would have to be reshot. However, using the algorithm outlined above we are able to process these data.

To test the accuracy of the algorithm before applying it to field data, synthetic data were generated to simulate the acquisition error described above. A single reflector was modeled, arbitrarily located to give an approximate incidence angle at channel 70 of 45°. Synthetic pressure and normal particle velocity data were generated for a streamer with a depth profile as shown in Figure 3.

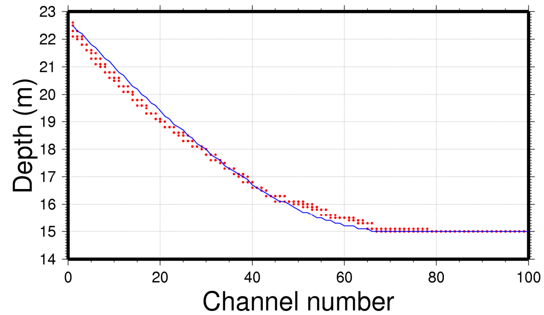

Figure 3: Streamer depth profile for six shots (red dots) and the approximation to this depth profile used for the synthetic modelling (blue line). Behind channel 70 the streamer depth was within acceptable tolerances.

These data were processed to simulate the up-and down-going pressure fields at an observation depth of 8m. The comparison with the modeled up- and down-going pressure fields is shown in Figure 4 which demonstrates that the process works well.

The procedure was then used to process shot gathers from the field data. The up-going pressure field obtained using this procedure is compared with the results obtained using a horizontal streamer assumption in Figure 5. The discrepancies between the two sections are confined to the first 70 channels as expected. Note that, for dual-sensor towed streamer data, the low frequency part of the particle velocity record must be rebuilt from the hydrophone due to high noise levels as described by Carlson et. al. (2007). For the purposes of this study, a high-pass filter has been applied to remove the frequencies for which this process is normally required so that the comparative sections demonstrate directly the performance of the wavefield separation and extrapolation algorithm with which this paper is concerned.

Conclusions

We have developed a space-frequency domain method for processing dual-sensor towed streamer data that allows irregular streamer profiles to be handled. This is an extension of the frequency-wavenumber domain processing sequence previously described by Carlson et al. (2007). The method was verified using synthetic data and applied to field data that were acquired with streamer depth variations far outside normally acceptable tolerances.

Acknowledgments

We thank PGS for permission to publish this work and all our colleagues who contributed with valuable comments, suggestions, and discussions.

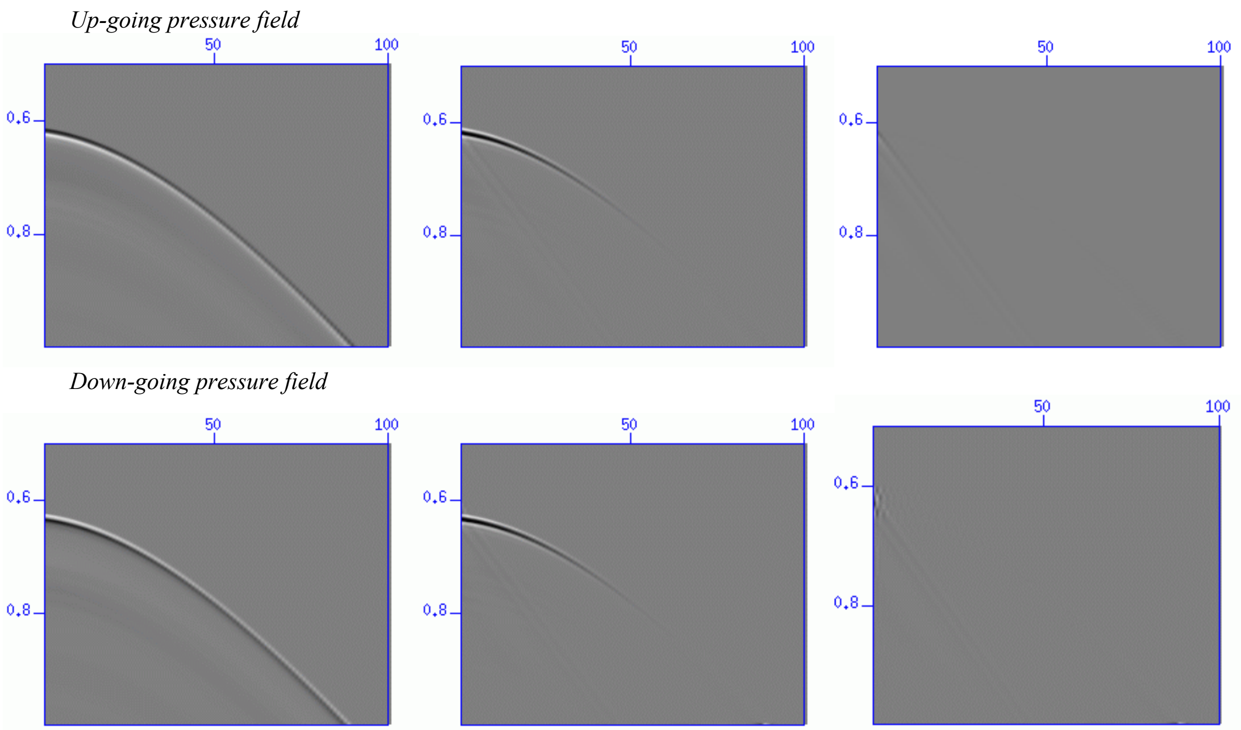

Figure 4: Left: modelled up- and down-going pressure field at 8m observation depth. Data are shown for channels 1-100 from 0.5 to 1.0s TWT. Center: difference between modelled results and those obtained from wavefield separation using a constant depth of 15m follwed by extrapolation to 8m depth. Right: difference between modelled results and those obtained from wavefield seaparation using the true streamer depth.

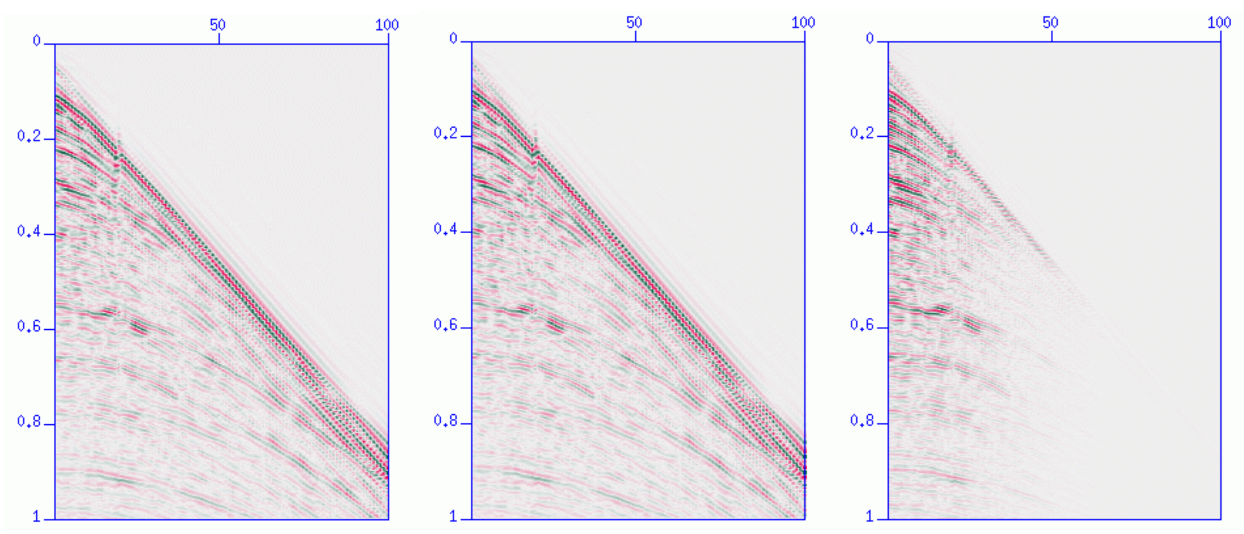

Figure 5: Up-going pressure field for a live shot gather processed using the true irregular streamer profile (left) and with a flat streamer assumption (center). The difference between the two sections is shown on the right.

EDITED REFERENCES

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