3D Shallow Target Imaging from Separated Wavefields

C. Castillo* (EOST/PGS) & W. Söllner (PGS)

SUMMARY

In marine seismic imaging, acquisition related footprints often contaminate the shallow parts of the subsurface. A main challenge today is to find new acquisition and imaging techniques in order to suppress those footprints. In this work, we firstly studied the influence of streamer spread related footprints and showed how these effects can be suppressed by imaging of separated wavefields. In this depth imaging approach, the up- and down-going wavefield components of dual-sensor data are separated and the receiver side ghosts (of primaries and sea surface multiples) are included as secondary sources in the imaging algorithm. Based on shallow water data from the North Sea, we show effective reduction of footprints and clear increase of resolution.

Introduction

Imaging the shallow parts of the subsurface from conventional 3D streamer data is challenging due to acquisition related footprint contamination. Therefore, new acquisition and imaging techniques are investigated to improve the image of shallow targets. Based on simultaneous recording of the pressure and velocity wavefields by a towed streamer system, the pressure and velocity wavefields are separated in their up and down-going wavefield components. This decomposition enables including sea-surface multiples in depth imaging algorithms (Muijs, et al., 2007; Whitmore et al., 2010; Lameloise, et al., 2012).

In this work, we predict the streamer spread related footprint from kinematic wavefield parameters and show how the footprint can be reduced by imaging the complete separated wavefields (imaging of primaries and multiples). This approach is validated based on real data acquired in the North Sea.

Acquisition footprints

Acquisition footprints are non-geologic amplitude effects that contaminate the seismic image, and may cause confusion in extracting geological information from amplitudes (Gesbert, 2002). Footprints are caused by acquisition related offset-azimuth irregularities and may be partly suppressed or in some cases even increased by data imaging.

In order to predict footprints related to the streamer spread limitation, we derived the edge effects introduced during the migration, considering finite and infinite spreads. Based on a Kirchhoff type migration and starting from the work of Sun (Sun, 1988), we derive the migrated image at points P of the subsurface, for an arbitrary source-receiver configuration. As our main interest is the effect of cross-line spread limitation, we limit our derivation to the 2D case. The migrated image can be expressed, in frequency domain, as:

$$O(P,\omega) = O(P,\omega)_{\infty}\left[1-\frac{1}{\sqrt{2}}e^{-i\nu\frac{\pi}{4}}\left(e^{i\frac{\pi}{2}C_1^2}\left(g(C_1)+i\nu f(C_1)\right)+e^{i\frac{\pi}{2}C_2^2}\left(g(C_2)+i\nu f(C_2)\right)\right)\right] \qquad (1)$$

Where $C_1 = a\sqrt{\frac{\left|\omega\tau''(\xi_s)_{\xi_s=0}\right|}{\pi}}$ and $C_2 = b\sqrt{\frac{\left|\omega\tau''(\xi_s)_{\xi_s=0}\right|}{\pi}}$ are parameters depending on the distance from P, to the edges a and b of the illumination area, $\tau''(\xi_s)$ is the difference of the second derivatives of the traveltimes (at the stationary point) between reflection and diffraction events, $\nu = sign(\omega\tau''(0))$ and ω is the angular frequency. The two polynomial functions g and f are introduced to approximate the Fresnel integrals (Abramowitz and Stegun, 1964). The term $O(P,\omega)_{\infty}$ denotes the migrated image for an infinite spread.

From Equation 1 we see how the ideal migrated image obtained considering an infinite migration aperture is affected by migration artefacts coming from both edges of the cross-line spread. Figure 1 shows the effects of the term inside the brackets of Equation 1, which may be considered as the artefact causing filter. We observe that edges of the illumination window perturb the signal and appear in the seismic images as footprints. We can also see that the amplitude of the signal increases when moving the migration window from the edge to the centre.

In conclusion, the streamer spread limitation causes on one hand additional events (migration “smiles”) in the image (which are generated at the subsurface illumination border), and amplitude alterations along the main imaging event, on the other hand.

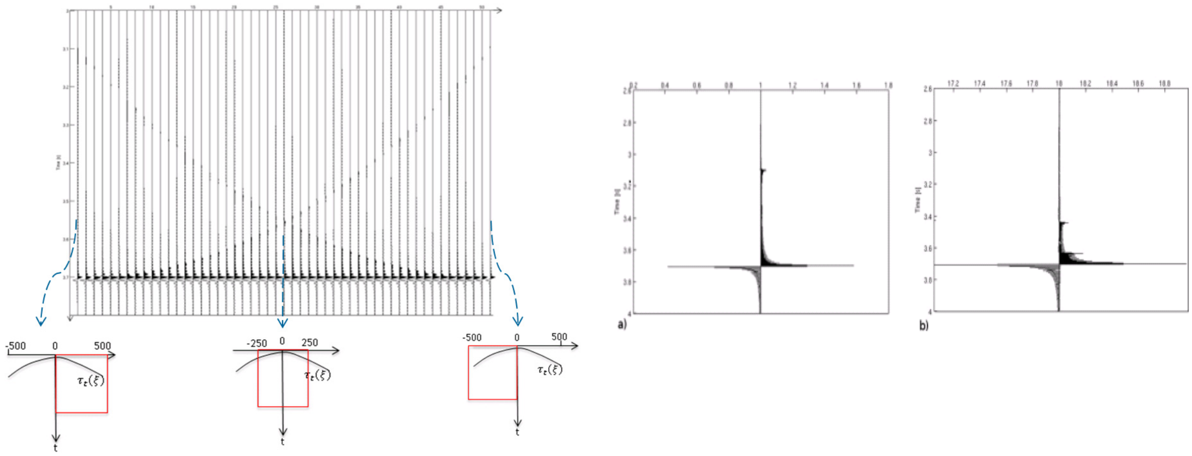

Figure 1 *Migration artefact for a moving migration window (left) with zoom of trace 1(right a) and trace 18 (right b).*

From previous studies (e.g., Whitmore, et al. 2010, Lameloise and Söllner, 2011) we know that multiples can produce better illumination than primaries. Due to the effect of secondary sources, generated by the down-going wavefield at every receiver position, the illumination area is generally extended from the midpoint to the receiver spread. That is why, in a new perspective, the multiples are treated as valuable information and included in imaging algorithms. To investigate the effect on the cross-line spread related artefacts suppression, we used the down-going pressure wavefield obtained from the dual-sensor streamer data, as additional source wavefields and perform imaging of multiple reflections.

Imaging using separated wavefields

The imaging technique, based on separated wavefields, is composed of three principal steps. The first step consists of separating the wavefield in the up and down-going components. Once this separation is performed, a wavefield extrapolation is applied to extrapolate the up-going and down-going pressure wavefields incrementally downwards into the subsurface. The last step consists of applying an adequate imaging condition, to extract the reflectivity information.

Using the simultaneous measurement of the pressure P and velocity wavefields V_z, the total pressure wavefield can be expressed as the sum of the up-going pressure wavefield P_U and the down-going pressure wavefield P_D (Amundsen et al., 1995; Carlson, 2007):

$$P_U = \frac{1}{2}\left(P - \frac{\omega\rho}{k_z} V_z\right) \quad \text{and} \quad P_D = \frac{1}{2}\left(P + \frac{\omega\rho}{k_z} V_z\right) \tag{2}$$

In Equation 2, ω, ρ, and k_z are respectively the angular frequency, the density, and the vertical wavenumber.

Using a Fourier finite-difference migration (Ristow and Rühl, 1994), the decomposed pressure wavefields are downward extrapolated to the subsurface. This method is based on the application of a phase shift operator in a constant background velocity, and an optimized finite-difference operator, for the laterally varying part of the velocity field.

Finally, an adequate imaging condition, following Claerbout's principle (Claerbout, 1971) is applied. As in imaging using multiples the source and receiver wavefields consist of complete down-going and complete up-going wavefields, undesired interactions called cross-talk noise are more likely to appear (Muijs et al., 2007). These cross-talk artefacts are generated by interferences between up and down-going events, which are not associated with the same subsurface reflecting point. In this case, an adequate imaging condition is the deconvolution imaging condition, which uses the quotient of the up-going wavefield (as receiver wavefield) divided by the down-going wavefield (as source wavefield). A multiplication by the complex conjugate of the down-going wavefield, a prewhitening term ε (Valenciano et al., 2003) and a smoothing operator $\langle\ \rangle$ (Guitton et al., 2007) may be included to stabilize this equation:

$$R(x,z) = \sum_{x_s} \sum_{j=1}^{N} \frac{P_U(x,z,_{x} x_s,\omega_j)\overline{P_D(x,z,_{x} x_s,\omega_j)}}{\left\langle \overline{P_D}(x,z,_{x} x_s,\omega_j) P_D(x,z,_{x} x_s,\omega_j) \right\rangle + \varepsilon(x,z,_{x} x_s)^2} \tag{3}$$

Using the deconvolution imaging condition in Equation 3 helps suppressing cross-talk in separated wavefield imaging (Whitmore, et al. 2010).

Data application

In April 2011, PGS acquired dual-sensor streamer data in the North Sea, with shallow water depth. In order, to test the benefits of using multiple reflections for improving the image of shallow targets and, in particular, attenuate cross-line spread related footprint effects, we compare results obtained in imaging using the primaries with those obtained using multiples, on three adjacent sail-lines. Firstly, for imaging of primaries we used the up-going wavefield as a receiver wavefield and an analytic source as the source wavefield. And, secondly, in imaging of multiples, we kept the same receiver wavefield, but replaced the analytic source by the down-going wavefield. We then performed the two Fourier finite-difference migrations. Figure 2 shows a comparison of cross-line images for the same sail-line selection. Looking at the cross-line section obtained using primaries we see footprint holes between each sail-line, especially visible in the shallow parts of the image. We also notice typical migration smiles at the left and right border of the three sail-lines. All these effects are much less visible in the image obtained using multiples. The surface related multiples introduced as secondary sources, add small migration angles at the outer streamers which contribute in closing the footprint holes. But, we noticed also more perturbations in the image, due to cross-talk noise that had not been reduced sufficiently in our imaging.

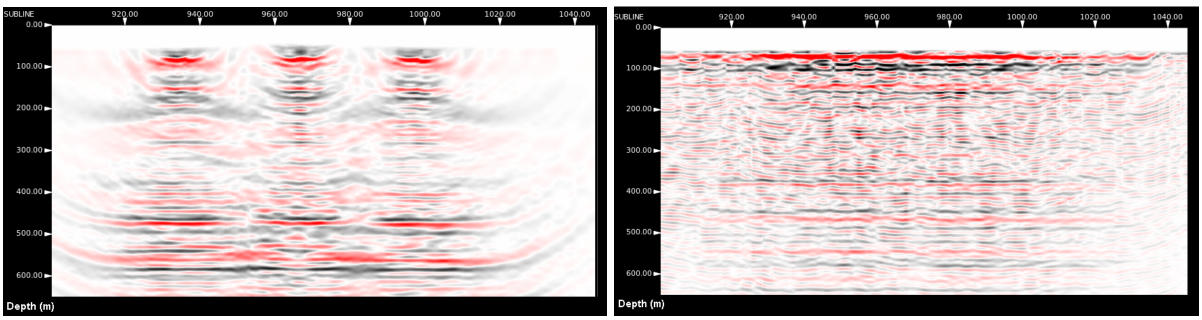

Figure 2 *Image of a cross-line section, after migration using the primaries (left) and using the multiples (right), for three adjacent sail-lines.*

Figure 3 shows a comparison of depth slices, situated at the water bottom level. The difference of illumination between the image of primaries and image of multiples is obvious. We can clearly see that the multiples provide a laterally more uniform illumination of the shallow targets. In the image obtained using only primaries, the aperture related footprints between sail-lines are strongly visible, which are, in contrast, not visible in the image of multiples. Moreover, shallow channels (marked in red) are continuously imaged across the sail-lines.

Conclusions

Streamer cross-line spread limitation is one of the major factors causing acquisition footprints in shallow target imaging. To understand how footprint artefacts are related to the subsurface illumination width, we derived an artefact prediction filter which is using kinematic wavefield parameters.

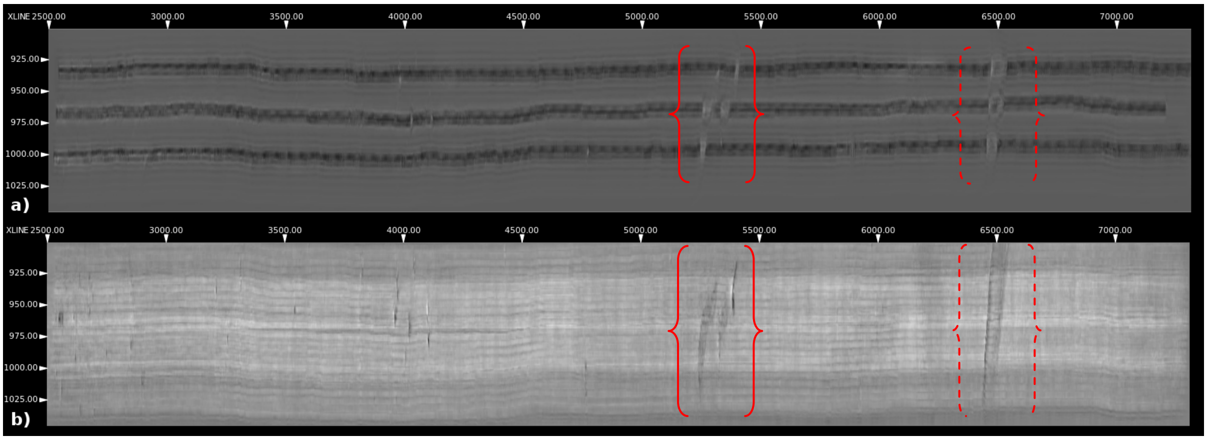

Figure 3 Depth slice at the water bottom level (z=69.5 m), for three sail-lines stacked together; a) in imaging primaries, b) in imaging multiples.

We applied imaging of primaries and imaging of multiples on shallow water data of the North Sea and compared the results. We observed strong footprint suppression in imaging of multiples, due to increased illumination width. This led to resolution improvement for shallow targets and consequently to a more accurate interpretation of shallow channels. However, acquisition related imaging artefacts and cross-talk noise could not be entirely suppressed. On-going investigations are directed towards improvement of our suppression techniques.

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