Synchronized multi-level source, a robust broadband marine solution

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Summary

The quest for robust broadband acquisition has become the cornerstone for obtaining high resolution images of the subsurface. The ghost diversity generated by variable depth streamer deployment creates the condition for processing to unlock the receiver ghost limit imposed by the depth of flat cables. Synchronized multi-level sources provide robust mitigation of source ghost effects by generating notchless wavefronts and make possible the source designature for the full bandwidth, a sine qua non condition for broadband images. Moreover, an optimized 3D distribution of airgun volumes provide the necessary omnidirectional pattern required for a 3D marine source array.
The imaging results obtained thanks to seismic acquisition combining variable depth streamer with synchronized source array show extra-large bandwidths where the only remaining frequency limit is the time sample interval.

Introduction

Variable depth streamer acquisition opened a large perspective for generating high resolution broadband images (Soubaras and Dowle, 2010). The average depth streamers at the range of 40 m and the joint deconvolution are the key elements for low frequency images down to 2.5 Hz. The receiver-ghost-free prestack gathers show broadband consistency up to the source ghost limit. However, to remove all acquisition limitations imposed by the free water surface, the elaboration of a source-ghost-free solution is necessary.
When an array of airguns releases the energy in the water, the spectrum of the emitted signal is very broad (Figure 1), but the interference of the downgoing wavefield with the reflection at water surface of upgoing waves generated by the same source, causes notches in the spectra for frequencies proportional to the inverse of airgun depths (e.1):

$$f_n = n\frac{v}{2z} \quad n = 1,2,\ldots \qquad \text{(e.1)}$$

where v is water velocity and z the gun depth

Undoing the interference of primary and ghost wavefields allows to remove the notches from the spectra by recovering the initial energy released by airguns. The separation of upgoing and downgoing wavefields could be achieved by recording complementary seismic data with sources rigged at different depths (Parkes & Hegna, 2012).
Shooting sequentially with dual sources at different depths creates the condition for performing wavefield separation and finally recovering the initial spectrum of airguns (Egan, 2007). However, the sequential shooting does not lead to the ideal condition where two datasets are acquired at the same locations.

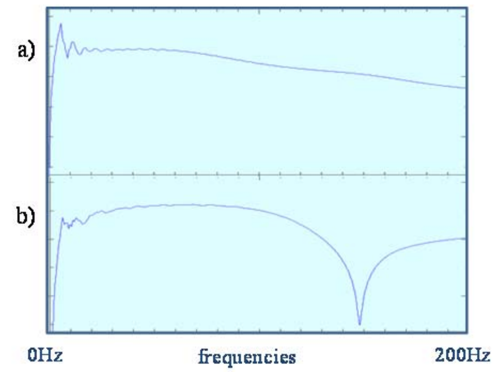

Figure 1: Amplitude spectra of a marine source:
a) without free water surface
b) with the ghost mask caused by the free water surface

A possible way to overcome this situation is to shoot both the "over" and "under" sources simultaneously. To achieve the separation of over and under wavefields, a deblending of the simultaneously shot dataset is necessary so that the over/under deghosting can be pursued. But this source deghosting approach could be affected by the deblending limitation of lowest frequency caused by time dithering of simultaneous sources (Abma, 2012).
To avoid all issues related to the de-synchronization of sources at different depth levels, we propose in this paper to show the broadband benefits of synchronized multi-level airguns.

Synchronized multi-level source array

When two airguns deployed at the same level are shot at the same time, the respective reflected wavefield at the free

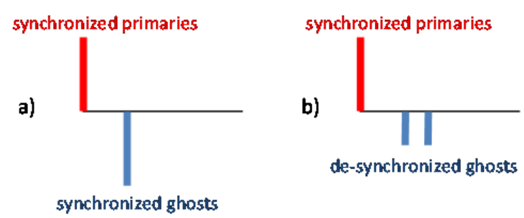

Figure 2: Primaries and ghosts of two synchronized airguns
a) airguns at same depth
b) airguns at two different depths

surface (ghosts) are synchronized by producing a pick of energy as important as the generated primary. Only the amplitude flips the sign due to the negative reflection coefficient of the water surface. However, if the two airguns are deployed at different depths and the deeper gun shots with the exact delay of traveltime between the two depth-layers, both downgoing wavefields will be synchronized while their respective ghosts will be de-synchronized (Figure 2).

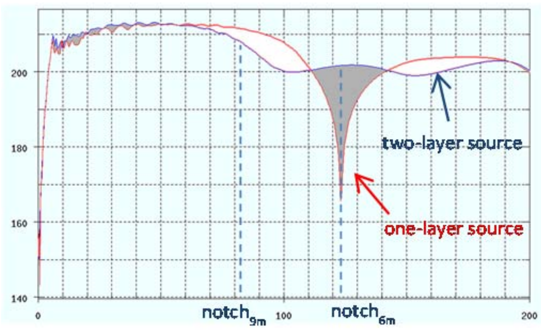

Figure 3. Amplitude spectra gain of synchronized two-level source array with airguns at 6 m and 9 m.

The advantage of de-synchronized ghosts with well-tuned time delays lies in the resulting capability to build a notchless residual ghost-mask. The optimum depths for the airguns are achieved where the notches caused by one gun correspond to the maximum of energies for the next. Figure 3 shows the spectral output of a source array with airguns deployed at 6-m and 9-m depths with 2-ms time delays between them. The ghost notch of a one-layer source array (6 m) is perfectly filled and, moreover, the extra low frequencies generated by 9-m airguns are visible.

The main interest of such as source is its ability to

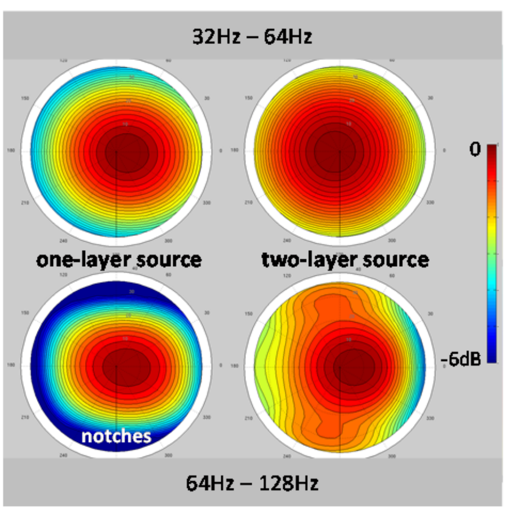

Figure 4: Frequency bandwidth energy at each azimuth and incidence angle: standard (left) vs. broadband source (right).

propagate ghostfree wavefields that do not require a source deghosting strategy during processing. However, to give such a source all the attributes of a conventional source, its multi-layer nature should not introduce directivity imprints. The most obvious choice of multi-layer-source-set consists of subarrays rigged at different depths, but this geometry has a strong directivity imprint. A 3D spatial distribution of airguns across the layer-depths is necessary to optimize the directivity, or at least to maintain the same directivity quality as for standard source arrays. Figure 4 shows an assessment of this optimization process by comparing the propagated energy between a standard source and a synchronized two-layer source for different azimuths and incidence angles. The directivity pattern of the new source remains at the same quality range even for frequencies corresponding to the one-layer source notch.

Far field estimation and source designature

The multi-level source allows defocusing of the ghosts, but they still exist. Nevertheless, the absence of notches in the spectra allows a successful designature of the seismic along the full bandwidth. This process requires an accurate estimation of source signature, which is not straightforward when it comes to multi-layer sources.

The calculation of far-field for synchronized multi-layer sources transgresses several main assumptions of pressure field modeling such as constant hydrostatic pressure around guns when the pressured air is released. In fact, the deep guns go off at the exact time that the pressure field generated by the shallow guns reaches them. The accuracy of this modeling is sufficient for source array design, but not necessarily accurate enough for building source designature operators.

A better approach is the use of near-field records. Ni et al, 2012 showed that accuracy of far-field reconstruction can be improved thanks to non-spherical considerations. However, near-field hydrophones have to be installed properly to avoid interference due to the multi-layer nature of this source. Another advantage of this acquisition-based approach is a more accurate estimation of the bubble effect

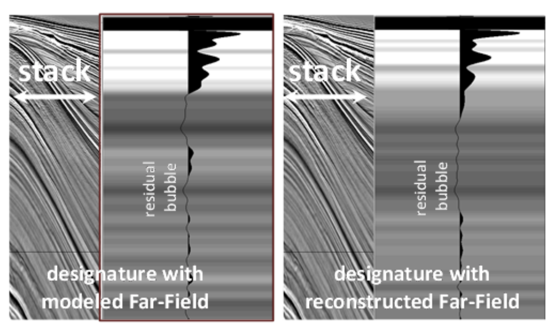

Figure 5: Remaining wavelet after designature with far-fields obtained by modeling vs. reconstructed from near-fields

and low frequencies in general, which are fundamental for broadband acquisition with variable depth streamers (Rebert et al, 2012).

Figure 5 illustrates the effect of an accurate designature on the residual bubble, which generally causes low frequency artifacts.

The far-field can be accurately extracted from water bottom reflection, but special conditions must be fulfilled. For a successful stack without reflectivity of the subsurface, the geology below the sediments has to be discordant with the topography of water bottom. At the same time, a deep water context is mandatory, otherwise the multiples will contaminate the far-field estimation. Practice showed that when those conditions are satisfied, the results of source designature are very satisfactory.

Of course in situ far-field measurement potential should not be neglected, but this process cannot be imbedded in a regular seismic acquisition. Firstly, the water depth has to be twice as deep as for the previous technique. The hydrophones have to avoid the water bottom multiple and at the same time be more than 150 m below the source to avoid near-field influence. Secondly, the far-field acquisition setup has to be stable below the source and with an acquisition speed faster than the 4 knots, necessary to maintain the seismic spread, cannot be supported. We consider in situ measurement important for the calibration of other far-field estimation methods but not realistic for a joint far-field measurement with seismic acquisition.

Acquiring with a synchronized multi-level source

A synchronized multi-level source is a compact solution for acquiring broadband data with variable depth steamers. A three-string rigging allows its deployment in the dual-source mode necessary for 3D broadband surveys (Figure 6). Five different acquisitions already demonstrated its robustness. A companion paper (Sablon et al., 2013) shows the benefits of this acquisition technique: ghost free images with an extra-large bandwidth from 2.5 Hz to 200 Hz. Figure 7 illustrates the observed image bandwidth when the water surface ghosts are removed via the processing of seismic data acquired with variable depth streamers and a synchronized multi-level source.

The joint deconvolution approach (Soubaras, 2012) does not just remove the receiver ghost effect, but at the same

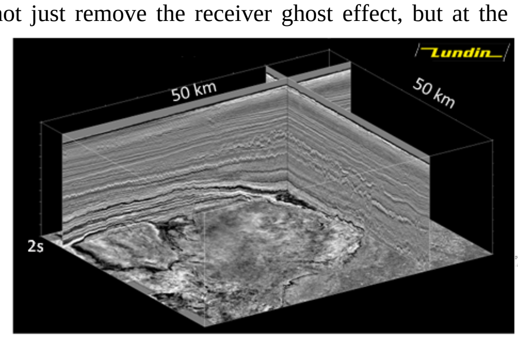

Figure 6. 3D Shallow water dataset offshore Norway. Data courtesy of Lundin

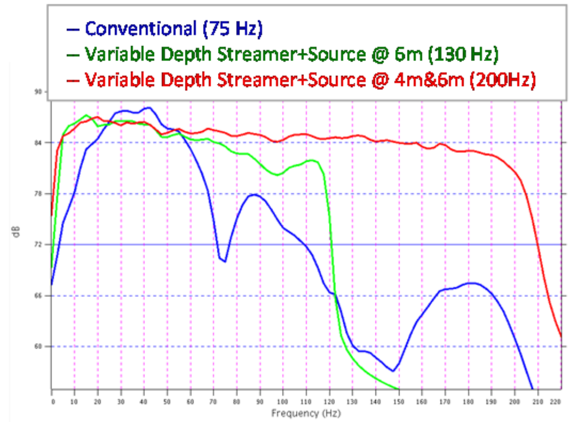

Figure 7: Comparative amplitude spectra of seismic images obtained with different type of acquisition. The combination of a variable depth streamer with a synchronized multi-level source allows a 7 octave-image-bandwidth.

time, the ghost reflection is migrated at its right location. This double illumination outcome of variable depth streamer imaging allows an increase of the spatial resolution at the same time as the temporal resolution naturally associated with the availability of wide frequency bandwidth. This spatial resolution can be verified when this type of broadband data is binned in a finer grid and processed accordingly. Figure 8 illustrates the tremendous resolution with visible polygonal faulting of shale sediments.

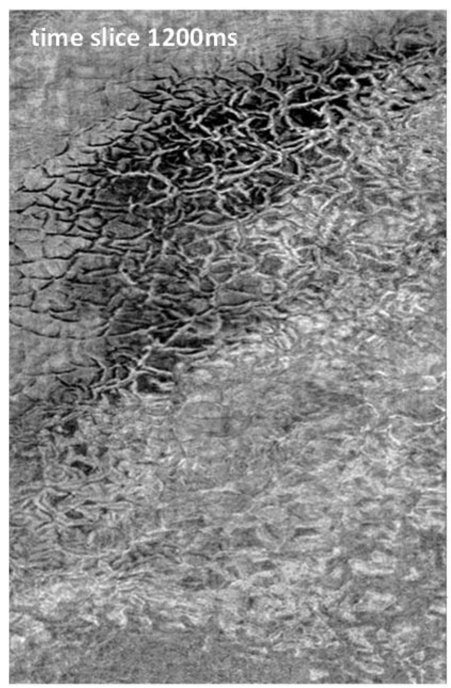

Figure 8: Imaging with 2 ms and fine binning (6.5 m x 9.325 m) of data acquired with variable depth streamers and a synchronized multi-level source. Data courtesy of Lundin

The use of a synchronized multi-level source simplifies the processing of variable depth streamer data for source-ghost removal and opens the possibility of performing an accurate, meaningful designature process, with better results than the usual multiple flows that combine de-bubbling, zero-phasing, and reshaping of the wavelet. Figure 9 summarizes the achievements in terms of image resolution due to the sharp lobe-less wavelets of 7-octave-bandwidth.

Conclusions

The synchronized multi-level source unlocks the source ghost limit and allows the variable-depth streamer acquisition to provide broadband seismic data reaching 200 Hz without compromising the low frequencies. This type of array has all the benefits of a standard marine source: robustness, directivity, repeatability, and mono/dual deployment, and it generates notchless wavefields by allowing an accurate designature process through the entire bandwidth thus encompassing residual deghosting, debubbling and zero-phasing in the same step.
Various acquisition experiences demonstrate the coherence of this source ghost-free solution.

Acknowledgements

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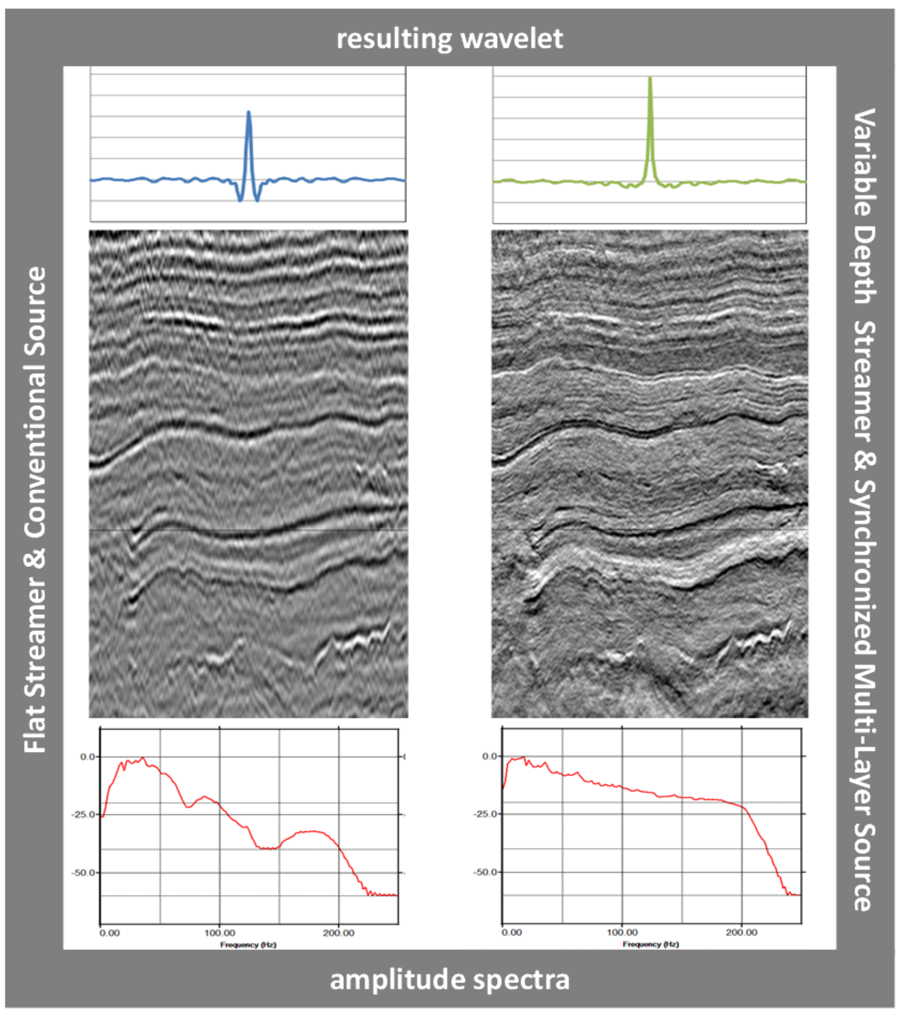

Figure 9: Comparison of images (middle), amplitude spectra (bottom) and their resulting zero-phase wavelet (top) acquired with:
- *flat streamer and conventional source (left)*
- *variable depth streamer and synchronized multi-level source (right). Data courtesy of Lundin*

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