Broadband processing in the Norwegian Barents Sea – practical aspects of deghosting in a challenging marine environment

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Summary

In 2013 TGS added additional coverage to its 3D database in the Norwegian Barents Sea over the Hoop and Finnmark Platform areas. Significant benefits are observed from the broadband processing of both new and previously acquired data through accurate deterministic deghosting and a deconvolution process, stabilized using large statistics. Sea conditions in the Barents Sea are rarely benign which can lead to unintentional variations in the streamer shape and depth. These variations can pose challenges for deterministic deghosting if the streamer is assumed to be flat and the sea surface reflection coefficient constant, as both are dynamic. A strategy is described to cope with such variations by combining deghosting techniques for flat and slanted streamer acquisition into a hybrid approach using examples from the Hoop area. In the Finnmark Platform area we correlate the ambient noise and streamer variation to observations on the sea state. By assigning the data into different quartiles the sea surface reflection coefficient can be estimated and varied as a seed for a stochastic search to find the most appropriate set of deghosting parameters.

Introduction

Conventional marine seismic data is affected by the interference from free surface ghosts on both the source and receiver sides. The natural diversity provided by propagation directions, depth variations, the sea surface not acting as a perfect mirror and significantly the use of solid streamers, means that the notches are not as deep as might be expected (e.g. Williams *et al*., 2012). We should therefore expect to retrieve valid signal within the notch frequencies above the noise floor without any additional effort in acquisition to diversify the receiver ghost notch by altering the streamer shape. To deghost seismic data and remove the deconstructive interference of the free surface ghosts deterministically we require accurate information for the source depth but more especially the receiver depths and the reflection coefficient at the sea surface. Inaccurate parameters generate artifacts in the form of ringing by deghosting in the wrong frequencies for a certain emergent angle. This can arise due to incorrect assumptions about the reflection coefficient and receiver depths.

The majority of acquisition to date in the Barents Sea has been acquired with a flat cable, with a typical source at 7 m depth and nominal streamer depth of 9 m. Figure 1 shows the outline of 3D TGS Barents Sea broadband projects, inclusive of the 2013 acquisition. Generally these data can be treated as flat streamer for deghosting purposes when acquired in low-to-moderate sea states (1-2 m of variation). Often the streamer depth is lowered in worsening conditions to continue acquisition, possibly generating an unintentional slant particularly over the first part of the cable. Slant effects become more acute on outer cables, which then violate the flat cable deghosting assumptions. In extreme cases we see variation of +/- 7 m of the nominal receiver depth and the associated notch ghost is highly diversified. In this situation the reflection coefficients are much lower than might be expected. Strategies are developed to overcome both situations through robust deghosting; combining techniques for a flat and slanted streamer, prestack redatuming, use of a stochastic searching element and large statistical deconvolution. Irrespective of acquisition challenges seamless broadband data can be generated. A brief overview of flat and slanted streamer deghosting, described in more detail by Masoomzadeh *et. al*., (2013), is given before introducing the hybrid approach.

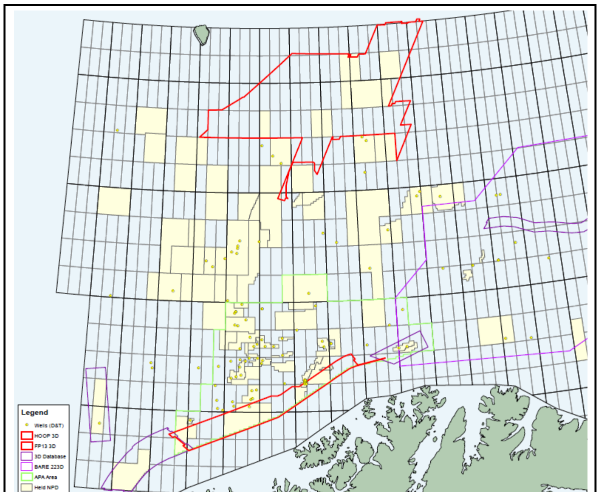

Figure 1: Outline of TGS 3D surveys in red covered by new broadband processing/reprocessing projects in the Norwegian Barents Sea. The Hoop area lies to the north and Finnmark Platform area to the south.

Flat streamer deghosting in the plane-wave domain

For flat marine streamer data, source and receiver ghosting in terms of a distinct time delay becomes a function of the angle of propagation. Deghosting is best performed in the *f-kx-ky*, or alternatively in the *τ-px-py* domain, representing a plane wave decomposition. After transformation, all seismic events along a single slowness trace share a certain ray parameter. Furthermore, the time delay between the main signal and its ghost remains invariant along the *τ* axis.

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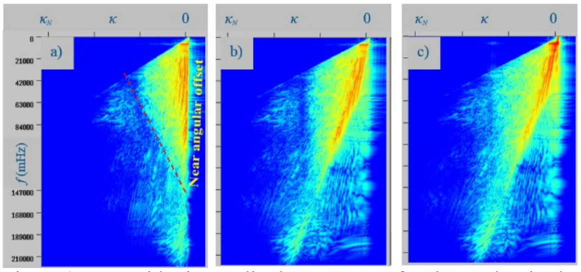

Figure 2: Logarithmic amplitude spectrum of a shot gather in the f-κ domain. a) A diagonal notch pattern, highlighted by a red dotted line extended from about 30 to 150 Hz, corresponding to the receiver depths of about 25 to 5m. b) A vertical notch pattern is observed when a coordinate shift to the intercept offset is applied prior to the τ-θ transformation. c) After the receiver side deghosting operation.

Formulation of a deghosting operator for both a constant source and receiver depth becomes relatively trivial in a deterministic sense, but in practice we might experience significant variations. In order to improve the deghosting result a stochastic search is performed for the most appropriate set of parameters, which include depths and frequency dependent reflection coefficients, assessing the autocorrelation for minimum energy. Using the depth information provided from acquisition we look in multiple gates and use empirical relations to define the reflection coefficient with respect to the angular frequency and slowness. Further improvements are achieved by applying a large scale statistical deconvolution, designed by averaging over potentially hundreds of shot gathers and numerous common slowness panels.

Slanted streamer deghosting in a shifted plane-wave domain

By slanting the streamer in acquisition there is the potential advantage of diversification through the mixing of incident angles and notch frequencies along the streamer such that the receiver ghost effect should largely cancel out at the point of stacking. In the prestack domain the data is not broadband unless correctly deghosted for both the source and receiver side. If the streamer is slanted by an angle of α, an up-going plane wave and its down-going ghost appear with different ray parameter, and the difference is angle dependent.

$$p_\alpha = \frac{\sin(\theta \pm \alpha)}{v} \approx p \pm \sqrt{1-p^2v^2}\,\frac{\sin\alpha}{v}. \qquad (1)$$

In the τ-θ domain, which is a variety of plane wave decomposition but where the horizontal axis is θ rather than slowness (p), the up-going and down-going wavefields appear with a uniform lateral separation of 2α. An angle shift can be used for the 'deslanting' task to redatum the data to sea level, so that conventional processing methods for a flat cable remain valid. Using a two-dimensional Fourier transform applied to the τ-θ domain, a ghost function can be expressed as:

$$1 + r_{(\omega,\tau,\theta,\kappa)} e^{i(\omega t + 2\kappa\alpha)}, \qquad (2)$$

where $\kappa = 2\pi/\lambda$ is angular wave-number and λ is angular-wavelength. As for the flat cable case, this can be complemented by a statistical stage to address the remaining spectral defects including residual ghosts, side

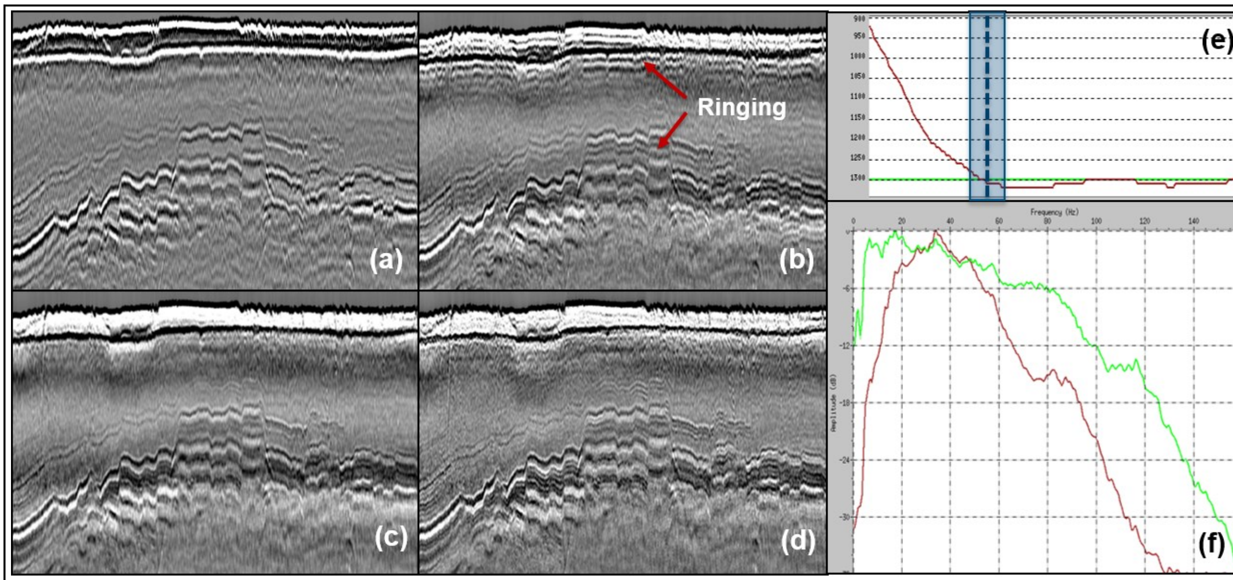

Figure 3: Example 2D subsurface line stack from reprocessed Hoop 2009 data where the cable depth was lowered. (a) Conventional input, (b) after deghosting assuming a constant streamer profile at 13 metres demonstrating ringing, (c) deghosting using the hybrid approach and (d) after large scale statistical deconvolution to address any remaining spectral defects; (e) shows the streamer profile out to an offset of ~ 2km and transistion from a slanted to flat profile is highlighted with the taper zone used. (f) Shows the normalized amplitude spectra of the input (red) compared to the output (green) after successful deghosting through the hybrid technique within the window of data shown.

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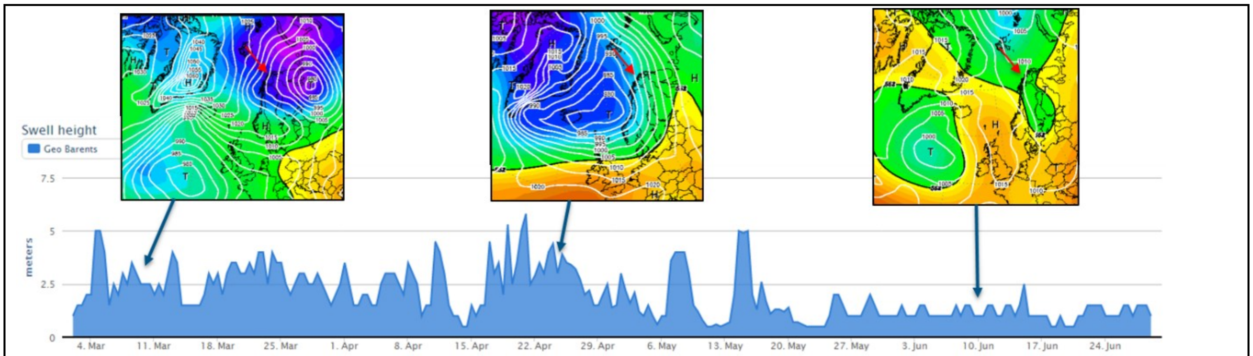

Figure 4: Recorded swell height during acquisition of the Finnmark Platform 2013 3D survey (FP13) which regularly exceeds 3m. The largest sea states coincide with deep Atlantic low pressure systems shown by the surface pressure charts from the GFS model archive (source: Wetterzentrale). The approximate location of the FP13 is highlighted by the red arrow.

lobes and bubble effect. Figure 2 demonstrates the receiver side deghosting process in the *f-κ* domain, which is the 2D Fourier transformation of the data in the *τ-θ* domain. Diagonal notches in the *f-κ* domain represent a combination of temporal and angular separations between primary and ghosted wavefields, whereas vertical notches represent a purely angular separation.

Hybrid approach

Advantage can be taken of both deghosting methods to address arbitrarily shaped streamers whether intentional or unintentional in acquisition. Provided receiver depth information is available the streamer can be segmented into linear portions and α automatically calculated. If there is no significant slant within a threshold for deghosting purposes the cable is considered flat, and a median value used for the initial stochastic search of the receiver depth. Source side deghosting remains the same irrespectively, as does the search for optimal reflection coefficients for the free surface ghosts on both sides. Consideration is given to the overlapping zone such that a taper is applied when recombining different portions of the deghosted shot gather after transformation back to the time and offset domain.

Data example from the Hoop area

In Figure 3 we demonstrate the benefits of the hybrid approach taken to correctly deghost all subsurface lines, focusing on shallow Jurassic targets in the Hoop area. It is observed an empirical set of deghosting parameters based on a flat cable assumption creates imperfections and ringing on the near offsets when the streamer was lowered to accommodate deteriorating sea conditions. This can manifest itself as fictitious events introduced on the stacked image in the form of ringing off strong reflectors such as the Base Quaternary that follows the water bottom (Figure 3(b)). Though deghosting in the *τ-θ* domain to deal with a locally slanted cable over the first few hundred meters of offset, we are able to improve the result further through the statistical process (Figure 3(d)). Interpretation is simplified by the removal of source and receiver ghosts with a greater richness in low frequencies.

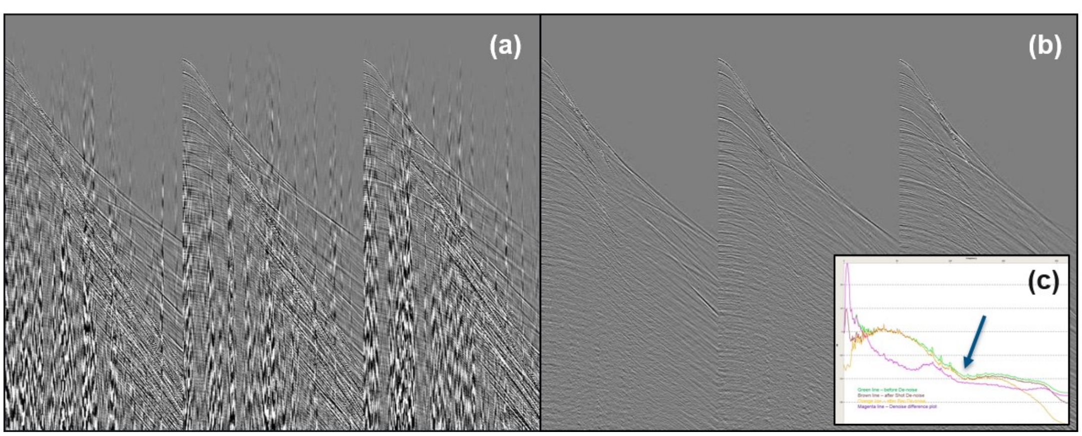

Figure 5: (a) Example shot gathers heavily contaminated with swell noise; (b) after swell noise attenuation and direct/refracted arrival removal in both shot and receiver domains. (c) Amplitude spectra of the the gathers before and after with the difference. The receiver notch highlighted by the arrow is spread across a broader range of frequencies than would normally be expected.

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Deghosting in a highly variable sea state – Finnmark Platform experience

In the Finnmark Platfrom area new 3D acquisition commenced in March 2013 for a period of approximately four months. Weather systems in the North Atlantic were unusually active at this latitude this time of year, giving rise to especially poor sea conditions (Figure 4). As a consequence many sequences were contaminated with high levels of low frequency swell noise. For broadband processing considerations this has to be removed prior to deghosting, because it will be boosted indiscriminately relative to the signal towards the shared source and receiver ghost notch at 0 Hz. Additionally, low frequency swell noise is undesirable to pass into the τ-p or τ-θ domains. After a debubbling operation, robust noise attenuation is applied in the shot and receiver domains prior to deterministic deghosting (Figure 5).

Significant streamer depth variations were observed on most sequences with the receiver notch heavily diversified; almost indiscernible after stack. Consequently, the reflection coefficient of the sea surface is low, so we partition the data into quartiles based on a noise measurement. This quality factor can be correlated to the observed sea state when the sequences were acquired (Figure 6). For each quartile we use a different starting reflection coefficient which is refined through the stochastic search. In this way we can achieve similar amplitude spectra after deghosting for all sequences, avoiding under or over boosting the notch frequencies which may generate ringing, and leaving less work for the statistical element to address.

Conclusions

Through robust deghosting and supplementary techniques, high quality broadband seismic data was generated in the Barents Sea on both new 3D acquisition and legacy data. Due to the imperfect reflection at the sea surface, and the natural notch diversity provided by the limited variations in the source and receiver depths, and more importantly, by the angle dependency of the delay times, the signal to noise ratio is often large enough to provide valid signal in a broad range of frequencies. Deterministic deghosting incorporating a stochastic search, followed by a deconvolution utilising large-scale statistics can effectively remove the ghosts, together with other spectral defects. We show that it is crucial to use an accurate set of parameters for both source and receiver sides, including the effective delay times for each ray parameter, and the effective reflection coefficients for each frequency, ray parameter and intercept time zone.

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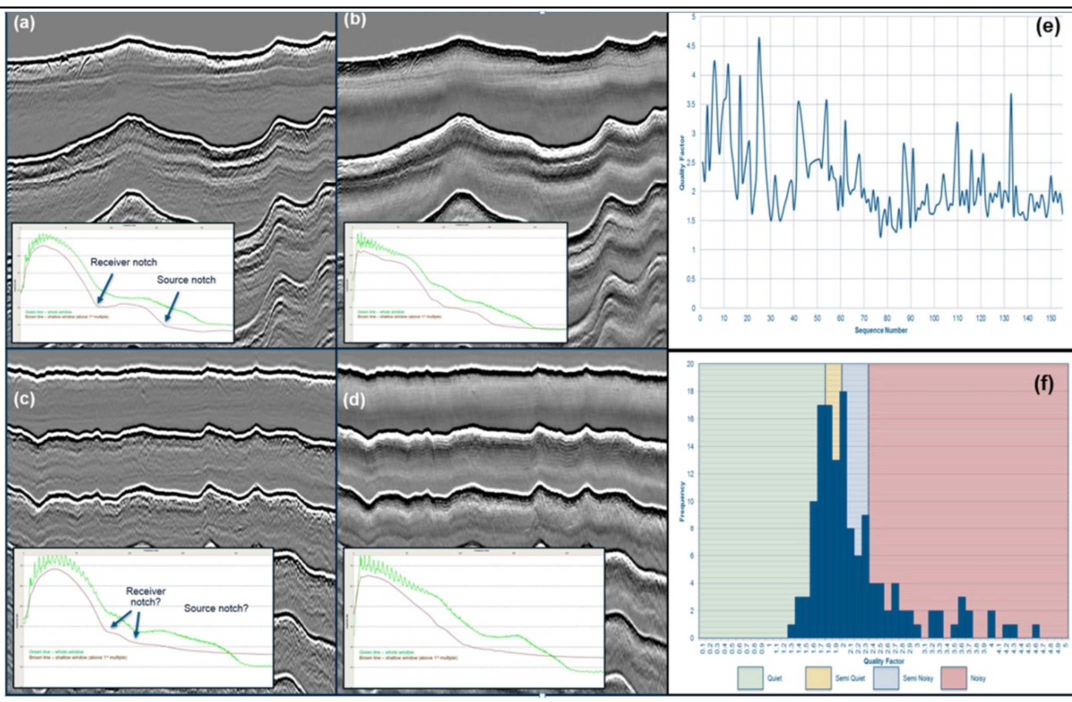

Figure 6: Varying the deghosting parameters based on a statistical measurement of noise. (a) Stack of a 'quiet' line before and (b) after deghosting with amplitude spectra above the strong water bottom multiple (red) and (green) full stack; (c) and (d) show the same for a 'noisy' line noting the reciever ghost notch is almost indiscernable and the source ghost invisible. (e) 'Quality Factor' derived from noise statistics correlating to the observed swell heights and (f), using this information to assign the data into quartiles to vary the deghosting parameters.

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EDITED REFERENCES

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