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Detailed Surface Multiple Prediction Using Split-spread Broadband Seismic Marine Data in a Complex Sea Floor Environment

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Summary

Seismic data for hydrocarbon exploration in the Barents Sea can be difficult to interpret because of severe contamination of the sections by residual diffracted multiples. These multiples mainly result from significant scars of the sea floor produced by paleo-iceberg drifts during glacial ages. To mitigate this problem, a new marine seismic design has been developed to acquire broadband, split-spread shot gathers with significantly improved sampling of the near offsets. This design allows for improved subsurface illumination which provides sharp and detailed imaging of subsurface reflectors, including the sea floor. To optimize the demultiple in this new data, we used several multiple models in simultaneous adaption procedures, including 3D SRME models, but also 3D wave-equation based multiple modeling to fully benefit from the available rich subsurface reflectivity representation. Along with this, an innovative and specific implementation of wave equation modelling enabled the construction of diffracted multiples “only” models. These separated models were fed into a multi-model adaptive subtraction using AVO-driven primary models as a constraint to preserve primary information (especially low frequencies). The ensemble lead to improved demultiple results.

Introduction

Seismic imaging in the Barents Sea remains a challenging problem because of the hard, irregular water bottom, which generates complex diffracted multiples. A new marine seismic design was developed to overcome this specific issue. It consists of acquiring broadband split-spread seismic data including zero-offset. In addition to offering improved illumination insights for imaging purposes, these data offer a clear advantage for multiple modelling, especially model-based methods. Our purpose is to show the impact of this specific acquisition geometry on the multiple modeling processing stage, and its benefit for removing those multiples, especially diffracted multiples (and multiples of diffractions) that tend to hide structural details around the oil and gas exploration objectives. Concerning surface multiples related to the sea floor and close reflectors beneath, we choose (and justify) the use of model based wave-field modeling methods, including an innovative and specific implementation for modeling diffracted multiples into separate datasets. The separated multiple models are then supplied to a multi-model adaptive subtraction, thus better addressing the specific behaviour of each type of multiple events.

Description of broadband split-spread acquisition over Barents Sea:

A new seismic survey covering an area of 1950 km² has been acquired in the Barents Sea using a new marine broadband split-spread design, as shown in figure 1. It consists of one vessel upfront towing 14 solid cables with variable-depth streamers (from 8 to 50m depth, and 50 m cable separation), while the source vessel is located in the middle of the seismic spread, with a triple source shooting every 3 s with continuous recording.

This acquisition design allows for recording of:

- broadband data, owing to the variable-depth streamer
- high frequencies, owing to the 5 m source depth
- high-density seismic data with a nominal binning 6.25 m x 8.33 m, owing to the cable separation and the triple source configuration

Contrary to a conventional spread, the split-spread design allows for the recording of dual azimuth data (positive and negative offsets), with especially pure zero-offset and wide azimuth near-offset data.

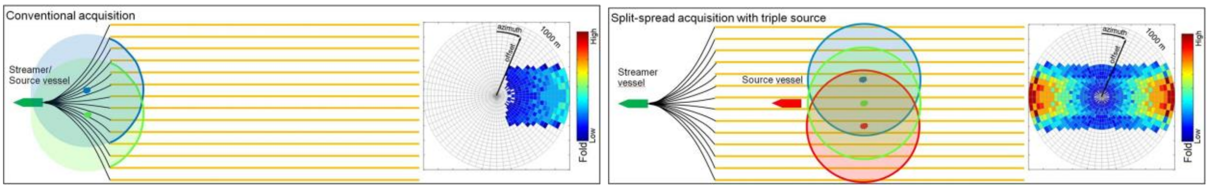
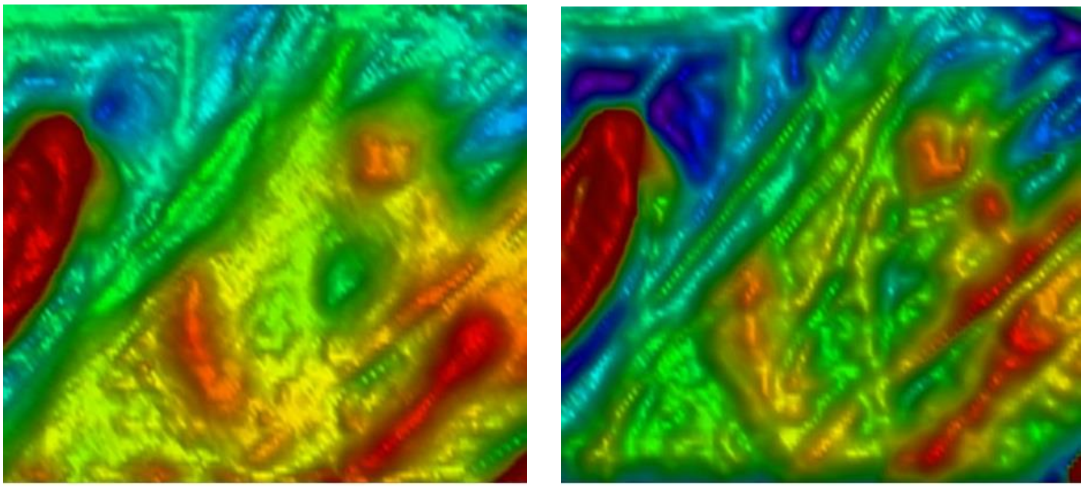


Figure 1: *Comparison of conventional spread and split-spread Acquisition*

3D multiple modelling on split-spread marine data:

The range of azimuths and offsets recorded with this type of marine data acquisition (as shown in figure 1), allows for the construction of very sharp migrated images in the shallow section (figure 2). Thus, we chose to use a model-based (surface-related) multiple modelling method (SRMM) for removing surface multiples related to sea floor vicinity reflectors, to benefit from the accuracy of the reflectivity models that can be built from this type of input data. The modelled multiples honor the precision of the reflectivity model; including its finer details, especially for modelling diffracted multiples (and/or multiples of the diffractions). This fidelity relies on the fact that information from every bin can be exploited with this kind of technique, without any issues related to coarser sampling of intermediate quantities or functions resulting from cost or data storage considerations. Those techniques are detailed by Pica et al. (2005), in the case of pure modeling methods. It models first primaries, P, then first order multiples from the previous result, $P \otimes P$, and along with others or higher orders, and for higher costs observably. It does not require data interpolation or extrapolation, but it is fully dependent for its kinematics on the propagation velocity that is used.



Conventional (vintage) *Split-spread*

Figure 2: *Examples of high-resolution water bottom: from conventional spread (left) and split-spread acquisition (right)*

An alternative model-based technique that was used, in addition to the previous one (for simultaneous multi-model adaptive subtraction), was presented and described by Weiser et al. (2006). It consists of a hybrid approach, where similarly to partial SRME, the data D, is “operated” with primaries P, by extrapolating it (in common shots or common receiver collections) within the water layer and by diffracting it from every point of the subsurface reflectivity model. This hybrid method is more robust with respect to velocities, but similarly to convolution SRME it requires to record or reconstruct recorded data, at least until the source position, and beyond toward negative offsets in the case of complex media. This extrapolation is needed to produce accurate multiple models in the short offsets ranges (that are unfortunately well stacked at the imaging stage). For reasonably complex media, this data extrapolation can be satisfactorily achieved by using the reciprocity properties approximated by flipping and altering the azimuth of the recorded data along sail lines. Unfortunately, this approximation with azimuth will fail when dealing with very complex structures, as shown in figure 3. In this figure we can observe that the extrapolated data significantly differ from actual recorded data as observed on the far cables. This is an important point in de-multiple processing quality. Acquiring split-spread data avoids the need for inaccurate extrapolation, enabling a more accurate multiple modelling, when dealing with complex sea floors.

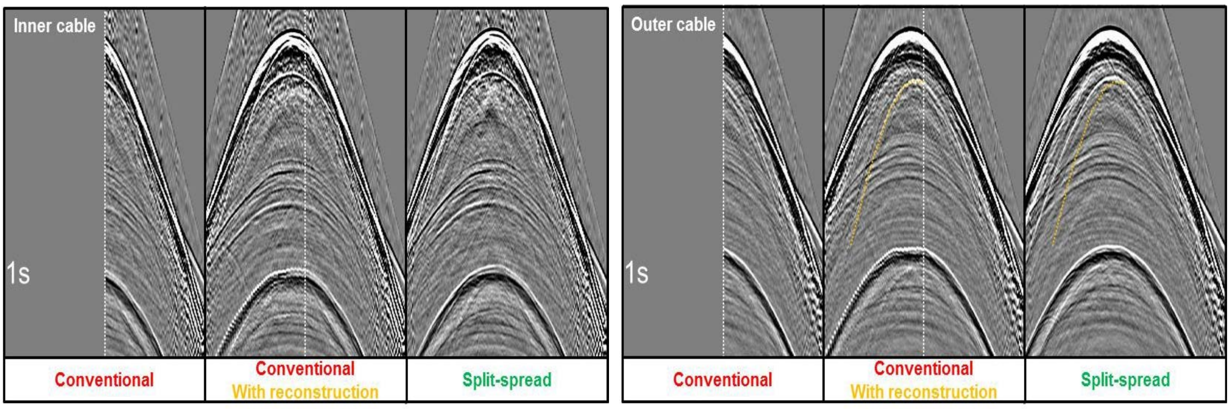
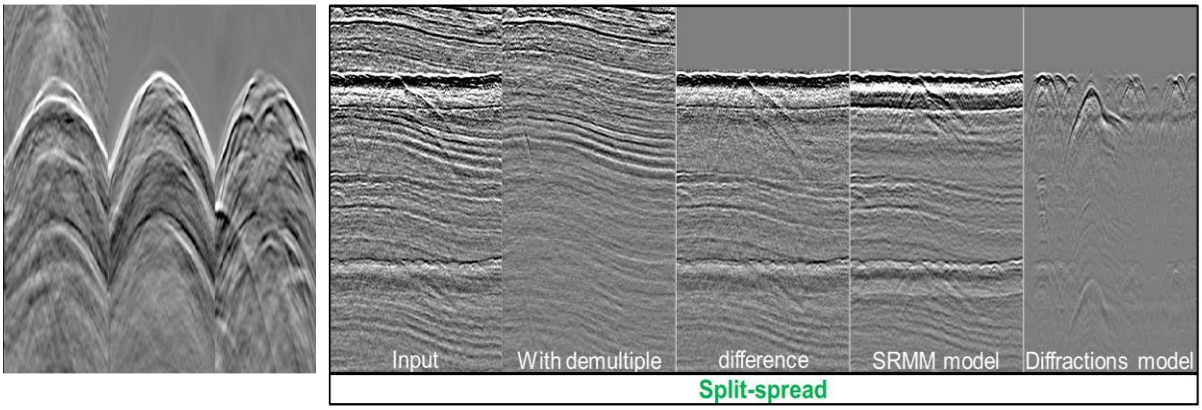


Figure 3: *Comparison between reciprocity-based extrapolated data from conventional spread and real recorded data of split-spread acquisition on far and inner cable. For inner cables (on the left), it works fine, but for far cables it fails as illustrated with the seismic event overlaid with the dashed orange curve.*

A new methodology for modelling diffracted (and triplicated) multiples only

Modeling and subtraction de-multiple methods can face challenges at the adaptation stage, if the amplitudes of modeled multiples do not fit those of the actual multiples along short spatial wavelengths. It may require designing short estimation windows for adapting the models, and thus putting in danger the integrity and preservation of primary information. For example, this can be the case when dealing with short period multiples if the relative amplitudes between different orders of multiples coexisting at the same location are not well handled, if the second order Backus type terms were missed (i.e. cost reasons for example). For this Barents Sea data example this was not the case, given that the sea floor was not shallow enough to produce severe crosstalk issues between orders. Instead, we are dealing with multiple reverberations that are not very homogeneous, as it consists in reflected seismic events and diffracted seismic events (although the so-called "diffracted multiples" can be actual diffractions and/or small scale triplicated reflections). The kinematics behaviour and shapes are rather different, or the amplitudes, and even the spectral content. Although the resolution obtained at the imaging stage is excellent, it does not result from the integrations from minus-infinity to plus-infinity as in a mathematical exercise, so it can be suspected that relative amplitude disequilibria between the modeled multiple reflections and multiples diffractions cannot be properly handled. One way to cope with this uncertainty is to split the problem, similarly to Vershuur et al. (2007), by modelling the diffracted multiples separately, and incorporating both the full field model (reflected and diffracted multiples) and "diffracted" (and/or triplicated) multiples-only models into a multi-model adaptive subtraction (Figure 4). This goal can be achieved by detecting discontinuities (on the shape and/or on amplitudes) of the reflectivity sections for generating separated "diffracted" multiples model using specific reflectivity sections in the hybrid SRMM procedure.



data - model - diff. model

Figure 4: *on the left group, the recorded data on one common shot split-spread, the hybrid WE based conventional multiple model on the centre of the group, and the hybrid WE base diffracted multiples-only model on the right of the group.*
On the right group, common channel lines of the data: before multiples subtraction, after multiples model subtraction. The image on the centre represent the adapted multiples, followed the input SRMM hybrid model, and ending by the "diffractors-only" SRMM hybrid model.

Although this additional multiple model helped to improve the de-multiple quality, the models are still imprinted by the properties of the acquisition geometry. This resulted in obtaining higher efficiency of the adaptive subtraction when using split-spread data rather than with the (simulated) conventional geometry data (figure 5). On top of the issues mentioned earlier about the approximations related to reciprocity properties usage (already illustrated in figure 3), we could add the impact of the reflectivity sections accuracy (compared in figure 2).

Low frequency and primary-preservation

Final adaption (illustrated on figures 4 and 5) is performed using primary-preserving joint multiple attenuation (Sablon et al, 2016), which combines complementary SRME (convolution), WE SRMM and diffractions models, with an AVO-driven primary model. This method aims at preserving primary continuities and especially low frequencies below 10Hz.

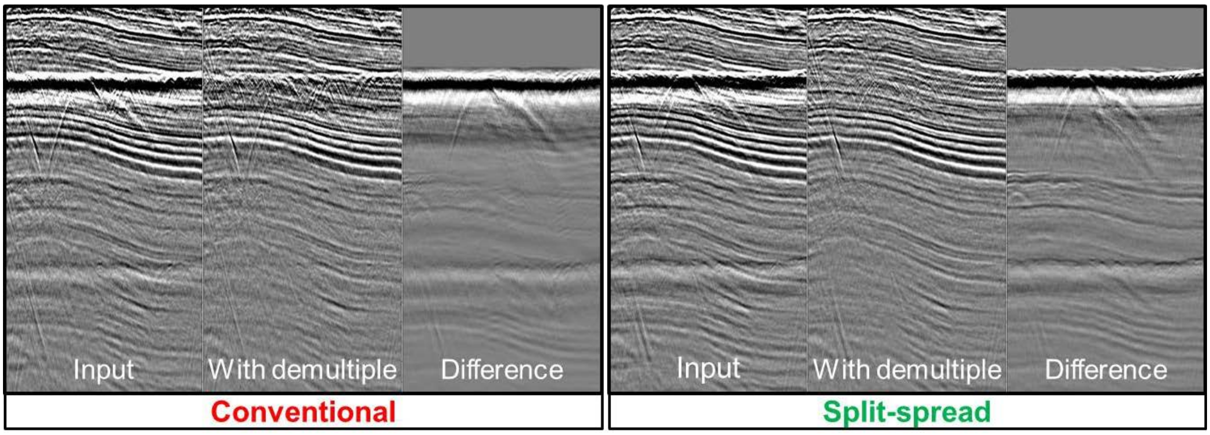


Figure 5: *Angle-stack 0-20 degree: from the data (left of the groups), after multiple subtraction (center), and the differences (right), in the case of conventional acquisition layout geometry (group left), compared to split-spread marine geometry (group right).*

Conclusions

Marine acquisition designed for recording split-spread broadband seismic data increases the efficiency of the de-multiple processing stage. This is shown on real marine data acquired in the Barents Sea. WE-based surface-related multiple modeling and subtraction benefits from the higher resolution of reflectivity sections built from the migrated data, and avoids erroneous approximations in reciprocity theorem usage and/or in data extrapolation to short and negative offsets. In addition a novel methodology producing an additional diffractions-only (and/or triplicated) multiple model was helpful for refining the results. Finally a subtraction strategy, involving the use of an AVO-driven primary model into the simultaneous multi-model adaptation, helped with the de-multiple efficiency, while preserving the primary information (particularly in the low frequencies range).

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