Removing multiples from the wide-angle wavefield

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The problem

At the continental margins of the north east Atlantic basaltic layers cover Tertiary sediments that are of interest for the exploration industry. Conventional seismic reflection methods fail in imaging through these high velocity layers due to their high reflection coefficient. Wide-angle seismic measurements with offsets up to 30 km contain more information about the subsurface in the form of refractions, turning rays and converted waves than standard seismic reflection data does. The main difficulty in analysing and processing this data is the correct identification of the individual events. Multiple reflections from the water bottom and the top of the basalt, as well as interbed multiples, mask the weak primary sub-basalt arrivals. Therefore multiple suppression in the far offset range is of great importance for sub-basalt imaging and a clear understanding and proper analysis of wide-angle data.

Our aim is to develop a new model-based iterative method to remove multiples and to apply this method to wide-angle test datasets. Firstly, common multiple suppression techniques were reviewed in order to assess how applicable they are in the far offset range. Following this review, first processing steps were applied to synthetic and real wide-angle datasets, using the industrial processing software ProMAX and the freeware code SeismicUnix from the Colorado School of Mines.

Multiple suppression techniques

Current multiple suppression techniques may be divided into the three general categories of NMO based methods, deconvolution and wave-equation demultiple methods.

NMO based methods

A large number of methods aim to separate multiples from primaries by exploiting their differences in moveout. First to mention here is simple NMO-stacking and the traditional f-k filtering method. F-k filtering is based on mapping primary and multiple energy in different quadrants of the f-k spectrum after the application of an intermediate moveout velocity (Yilmaz, 1987). Secondly, the Radon-transformation of NMO corrected gathers using hyperbolic stacking surfaces separates primary and multiple reflections that have different moveouts. The inverse transformation of selected parts of the data is used to remove multiple energy as described by Foster and Mosher (1992). These methods require sufficient moveout and therefore work best at larger offsets.

Deconvolution

The next category of techniques is based on the periodicity of events and makes use of predictive deconvolution (Wiener filtering). A precondition for the successful application of deconvolution for multiple suppression is that multiples are periodic whereas primaries are not. For multiples this assumption is only valid at zero-offset and for 1-D media. The zero-offset condition can be overcome by transforming the data into tau-p (ray-parameter - intercept-time) or slant-stack domain. Slant stack multiple suppression is based on the fact that multiples become periodic along each slanted stacking path (*i.e.* every p-value), but the technique remains limited to 1-D media. Lokshtanov (1999) proposed a data-consistent deconvolution with an operator for multiple suppression in the tau-p domain, taking both water-layer multiples and peg leg multiples into account. These different multiple events require different deconvolution operators. Lokshtanov (1999) claims that this technique is suited for multiples generated by a strong reflector below the seafloor, like a basalt layer within sediments. Lateral inhomogenities are taken into account with a multichannel operator.

Wave-equation demultiple

Finally, there are three different wavefield prediction and subtraction methods, based on the wave-equation. These are the wavefield extrapolation multiple suppression method (Wiggins, 1988), the feedback loop approach (Verschuur *et al.*, 1992), and the inverse scattering series method (Weglein *et al.*, 1997).

Wavefield extrapolation predicts seafloor and peg-leg multiples by modelling the wave propagation through the water layer and estimating the water-bottom reflectivity. The water depth is required as an additional input information. Where primaries and multiples occur close in time the reflectivity estimation may fail to discriminate between them.

The feedback loop and the inverse scattering series methods (also called free-surface multiple elimination methods) focus on the reflection of the wavefield at the free surface. Neither method requires knowledge about the subsurface below the receivers. The multiple elimination process is designed as an inversion in which the source and reflectivity properties of the subsurface are estimated. While both methods equal in the suppression of free-surface multiples they differ in their estimation of internal multiples.

All three methods require fully populated data sets. Missing data or poorly approximated missing data leads to inaccuracies in the predicted multiples, thus compromising the effectiveness of multiple removal. The very long offset two-ship datasets tend to have missing data in the near- and especially mid-offset range (due to separation between the ships) that has to be compensated for to apply free-surface multiple suppression methods.

A combination of multiple suppression methods for prestack processing was proposed by Zhou & Greenhalgh (1996). Wave-extrapolation is used to generate a model of free surface multiples from the measured seismic data. This modelled data, as well as the original data in the form of shot or CMP gathers, are transformed into the parabolic tau-p domain. In this domain primaries and multiples are separated by their different moveout. By comparing the energy on traces of the seismic input data and the modelled data, reject zones are automatically determined. The application of a filter gain function and the inverse transformation provides multiple suppression in the near as well as in the far offset ranges. Yilmaz (1989) recommends a t^2-stretching of the time axis of the shot/CMP-gathers before application of the parabolic Radon-transform, to transform the hyperbolic events into strictly parabolic events.

When considering the removal of multiples in the wide-angle range, we are confronted with several different types of multiples. As well as multiple reflections, multiple refractions occur and complicate the seismic analysis. Slant stacking could provide a separation of linear refractions and curved (hyperbolic) events. Hyperbolas on a CMP gather map onto ellipses in the tau-p gather, while linear events should map onto points. The principal idea for the suppression of multiple refractions is that points are easier to remove than linear structures. Besides predictive deconvolution, surgical muting could be used for the suppression of multiple energy in the transformed domain.

New insights may be gained by using the wavelet transform to analyse the data (Hubbard, 1996). Presently this technique is mainly used for data compression and few seismic signal processing techniques make use of this transform, even though it provides information beyond the Fourier-transformation. The main difficulty using the wavelet transform is the right selection of the particular wavelet used in the transformation. The possibility of adapting a wavelet to different frequencies and the time-frequency information contained in the transformed data may give new opportunities to address the multiple problem.

Processing applied to synthetic and real wide-angle data

Wide-angle multiple suppression techniques should be first tested on simple numerical models before they are applied to complex real data sets. Furthermore, the comparison of modelled and measured data allows the identification of individual events, such as P-wave primaries, converted waves (PSSP, PSPPSP etc.) and their multiples.

Synthetic data

Synthetic shot gathers from simple geological models were computed using the ProMAX finite difference modelling module. These gathers were used to test multiple suppression techniques in the tau-p domain (**Figure 1**).

After slant stacking of the data, surgical muting was applied to small areas at junction points of the ellipsoidal curves in order to remove multiples of the refractions, and the inverse transformed data studied. This technique takes only multiple refractions into consideration and is problematic because of the small differences in intercept time between primary and multiple refractions.

Since the ProMAX code does not take into account converted waves, a full waveform modelling technique for elastic wave propagation in inhomogeneous anisotropic media (Ji & Singh, 1999) will next be used to produce synthetic seismograms. These data will be studied to analyse the interactions of primary, converted and multiple energy.

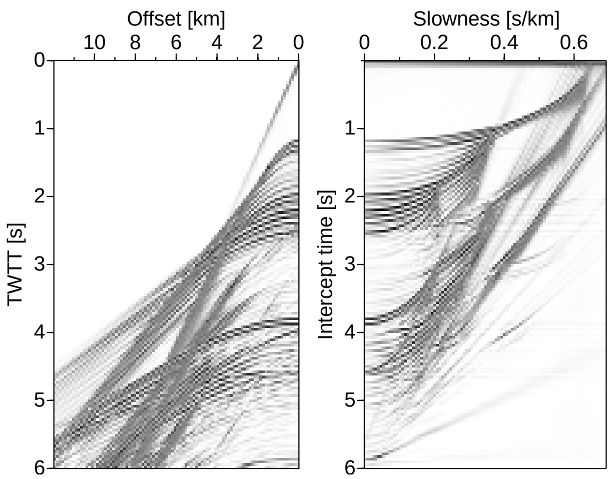

Figure 1. Synthetic gather (left) with high velocity layer (4500 m/s) between 2.1 and 2.6 s, an intermediate low velocity layer (2600 m/s) between 2.3 and 2.4s, the basement (6000 m/s) at 3.9 s, and its tau-p transform (right)

Real data

For the application of wide-angle multiple suppression techniques on real seismic data several datasets are available to the project. The BGS Rockall Consortium provided a two ship large aperture reflection profile that was collected in 1997. This profile has a full fold length of 278 km and consists of about 700 shot supergathers with offsets up to 30 km and a receiver interval of 25 m. It was recorded in a region where young volcanic flows cover the underlying Mesozoic sediments and obscure their structure. A further two-ship data set was made available by Amerada Hess and contains 760 shot supergathers with offsets up to 18 km. This profile was collected in the Shetland-Faeroes Basin.

First processing steps were restricted to the analysis of the Rockall data set. Stacks of different offset ranges as well as multiple suppression in the *f-k* and tau-p domain where investigated. A constant velocity stack of the nearer offset traces (up to 6 km) with seawater velocity was produced to accentuate seafloor multiples. Next, a preliminary velocity model was obtained using semblance and NMO analysis. These velocities were used for stacking of different offset ranges. The exclusion of the very near offsets (< 1 km) from stacking resulted in a good suppression of the seafloor multiples. NMO based multiple suppression was studied using *f-k* analysis and dip-filtering. Different reject and pass zones were defined in the *f-k* domain to suppress multiple and aliased energy.

In order to recognise refractions and their multiples in the tau-p domain, a top mute along the first reflection was picked on a long offset shot gather. After muting and transformation into the tau-p domain this gather was compared with the original transformed data and the refracted energy identified.

The near offset range (< 6 km) of the Rockall data set was prestack depth migrated. This enabled comparison with a prestack depth migration of the far offset range (6-18 km) as well as allowing the application of a interpretational velocity analysis in order to achieve an optimum depth model. A good depth model is required as input for ray-tracing in order to predict the arrival times of the primary events in the wide-angle range. The reconstruction of data in this manner helps understanding of the complex pattern of primary and multiple reflections and refractions at critical and postcritical offsets. Simultaneously, this approach could also be used for designing a rejection filter in the transform domains (*f-k*, tau-p) and could replace the wave-extrapolation method used by Zhou & Greenhalgh (1996) that only allows for the suppression of seafloor multiples.

Next steps

Synthetic wide-angle seismic data computed with the fast full waveform modelling technique of Ji & Singh (1999) will provide a starting-point for analysing the separation of primary and multiple wide-angle energy in different transform domains (*f-k*, tau-p).

A combination of different multiple suppression methods (NMO-stacking, deconvolution, and wave-equation demultiple), as proposed by Zhou & Greenhalgh (1994, 1996), will be used to define convenient filters in domains that are best suited to separate primary from multiple energy. Removing multiples in the transform domain involves the problem of defining the reject zone. This problem could be overcome by the forward modelling of multiples, and the application of this model to construct a filter, either in the tau-p or f-k domain. To achieve an efficient filtering technique the recognition of multiple energy in the transform domain must be automated.

Since we are dealing with different multiple events (free-surface and interbed multiples) as well as different wave propagation processes (reflected, refracted and converted waves), an iterative approach in different domains seems to be most promising. Further investigation will clarify whether additional information could be attained using wavelet transformation.

Acknowledgements

I thank Satish Singh, Penny Barton, Robert Hardy, Hamish Macintyre (Amerada Hess), Edgardo Di Nicola-Carena, Ying Ji, and fellow LITHOS students for useful discussions. This PhD studentship is fully funded by the LITHOS Consortium.

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