Tu N114 08

Estimation of Primaries by Sparse Inversion in Shallow Water - Practical Challenges and Strategies

X. Hu (CGG), J. Qin (CGG), J. Liu (CGG) & J. Hembd* (CGG)

SUMMARY

Estimation of primaries by sparse inversion (EPSI) is an iterative method that effectively separates primaries and surface-related multiples, especially in shallow water. Multiple attenuation in shallow water is challenging, mainly because of acquisition limitations. We propose a strategy for EPSI with the following objectives: (1) create an alternating picking method for the first iteration of EPSI that correctly separates primaries and multiples and also expedites the convergence in some cases and (2) pick only strong shallow reflectors to alleviate the cost while attacking most of multiples generated by those reflectors. We applied our method to two synthetic data sets. Then, we tested the EPSI method on a complex field data set to demonstrate that it can effectively attenuate multiples.

Introduction

The surface-related multiple elimination (SRME) method (Berkhout 1982; Verschuur et al. 1992) achieved great success and became the standard multiple removal technique in seismic data processing. However, it can suffer from missing near-offset data, especially in shallow water. Wang et al. (2011) proposed the model-based water-layer demultiple (MWD) method to address this issue and to assist SRME with predicting surface-related multiples. In 2009, van Groenestijn and Verschuur developed an approach for the estimation of primaries by sparse inversion (EPSI). EPSI inverts for both primaries and multiples to explain the input data. Unlike adaptive subtraction in SRME, which minimizes the primary energy, EPSI minimizes the unexplained part of the data.

Various adaptions have been proposed to improve EPSI (Baardman et al. 2010; Lopez and Verschuur 2012; Verschuur 2013; Lin and Herrmann 2013). In marine data, the first iteration of EPSI usually resolves the water bottom reflection. With this reflection resolved, EPSI can explain the water-bottom multiples, which are usually the strongest multiples in the data. We propose a new picking strategy for the first iteration that may avoid some pitfalls of the original EPSI picking method by van Groenestijn and Verschuur (2009) and reduce the total number of iterations. In the application on field data, there are two main challenges for EPSI: (1) the extremely high computational cost and (2) wrong picks caused by imperfect field data quality and data regularization. To address those challenges, instead of trying to predict all surface-related multiples, we only target multiples generated by the shallow strong reflectors. We applied our strategy to a complex synthetic data set as well as a field data set.

EPSI Theory and Method

The EPSI method estimates both primaries and multiples through an iterative inversion process. In the EPSI primary-multiple model, recorded up-going seismic data $\boldsymbol{D}$ can be expressed in the frequency domain as

$$\boldsymbol{D} = \boldsymbol{X}_0 S - \boldsymbol{X}_0 \boldsymbol{D}. \tag{1}$$

Here, $\boldsymbol{X}_0$ is the primary impulse response, S is the source wavelet, $\boldsymbol{X}_0 S$ is the primary term, and $-\boldsymbol{X}_0\boldsymbol{D}$ is the multiple term, where the minus sign comes from the water surface reflectivity. A key factor in the EPSI algorithm is the sparsity constraint on $\boldsymbol{X}_0$ in the time domain. Thus, we assume that $\boldsymbol{X}_0$ can be expressed as a limited number of spikes with relatively large amplitude. Equation 1 is solved by being formulated as a minimization problem. In contrast to the adaptive subtraction in SRME, where primary energy is minimized, EPSI minimizes the total residual energy. The primary impulse response $\boldsymbol{X}_0$ and source wavelet S are solved in an alternating manner with zero as their initial values.

In the first EPSI iteration, the steepest step $\Delta\boldsymbol{X}_0$ is the multi-dimensional correlation of input data $\boldsymbol{D}$ with itself. This can be interpreted as multiples in the input data being mapped to the positions of primaries. However, the auto-correlation also introduces spurious events in the shallow section, which are mapped from deep primaries. If the multiple energy is (partially) masked by the strong primaries in the time domain, the mapped primaries from multiples are also (partially) masked by these spurious events. This results in an incorrect sparse update $\Delta\boldsymbol{X}_0$.

Inspired by the above observation, we propose a new picking strategy for the first iteration of EPSI. Instead of picking on the auto-correlation, our method picks on the input data $\boldsymbol{D}$ directly with proper scaling to match the amplitude of $\Delta\boldsymbol{X}_0$. This is only done for the first iteration. With a correct sparse update $\Delta\boldsymbol{X}_0$ in the first iteration, we expect to expedite the convergence and to reach a better solution.

Synthetic Data Example

We tested EPSI with the modified update strategy on two synthetic data sets: (1) a simple flat layer example to demonstrate the challenge of multiples masked by primaries and (2) a complex example that more closely resembles a real-world data set.

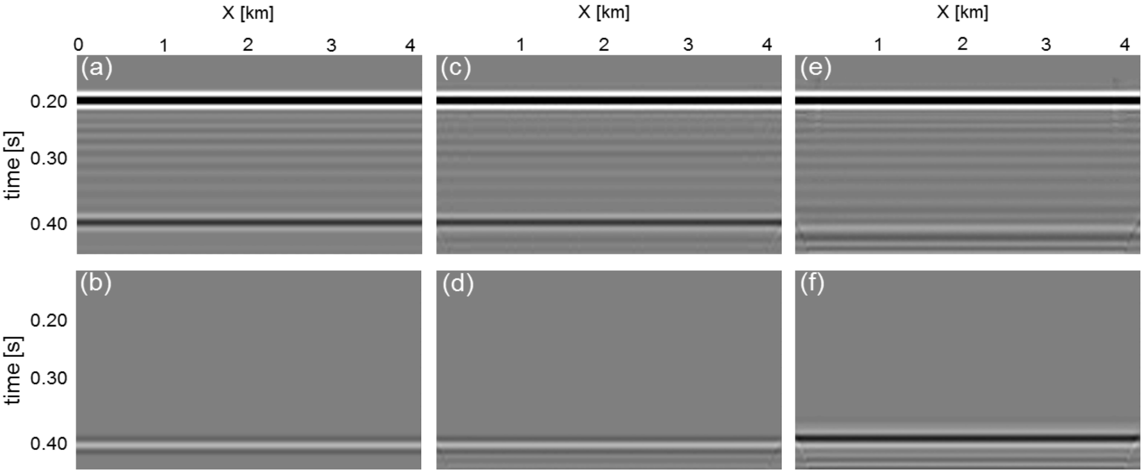

Figure 1 *Estimation of primaries by sparse inversion (EPSI) results on three-layer model. (a) True primary. (b) True multiple. (c) EPSI primary after eight iterations with picking on input for the first iteration. (d) EPSI multiple after eight iterations with picking on input for the first iteration. (e) EPSI primary after 50 iterations with picking on auto-correlation for the first iteration. (f) EPSI multiple after 50 iterations with picking on auto-correlation for the first iteration.*

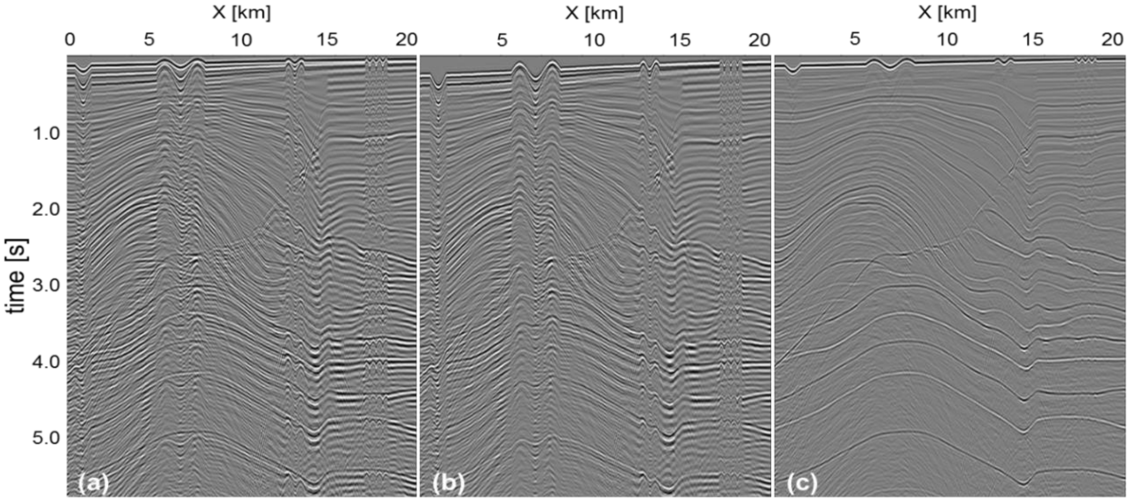

Figure 2 *2D synthetic data set with rugose water bottom. (a) Input near channel data. (b) Multiples after 60 iterations of EPSI. (c) Direct subtraction of multiple from input.*

In the case of picking on input, after eight iterations, we obtained excellent primaries (Figure 1c) and multiples (Figure 1d) with correct amplitude and timing compared with the true primary (Figure 1a) and multiple (Figure 1b). In contrast, when picking on auto-correlation, EPSI struggled to recover the first primary, distorting the source wavelet. As a result, EPSI explained the multiple incorrectly. In the later iterations, EPSI tried to correct the primary impulse $\boldsymbol{x}_0$ and source wavelet s driven by the residual. After 50 iterations, EPSI was able to obtain the correct primaries from the first reflector. However, the primaries from the second reflector were incorrect (Figure 1e). In fact, EPSI incorrectly explained the primaries from the second reflector as multiples after 50 iterations (Figure 1f). The residual is too small to drive the self-correction mechanism, so further iterations would not continue correcting the primaries.

The second synthetic data set was comprised of a 2D model from a shallow water environment with water depths ranging from 30-100 m (Figure 2). Additional features were added to the water bottom to test the effectiveness of demultiple with varying degrees of water bottom rugosity. In near-channel data before EPSI (Figure 2a), the multiple reverberations from the water bottom features superimposed an oscillating pattern on the deeper reflectors, masking the true events.

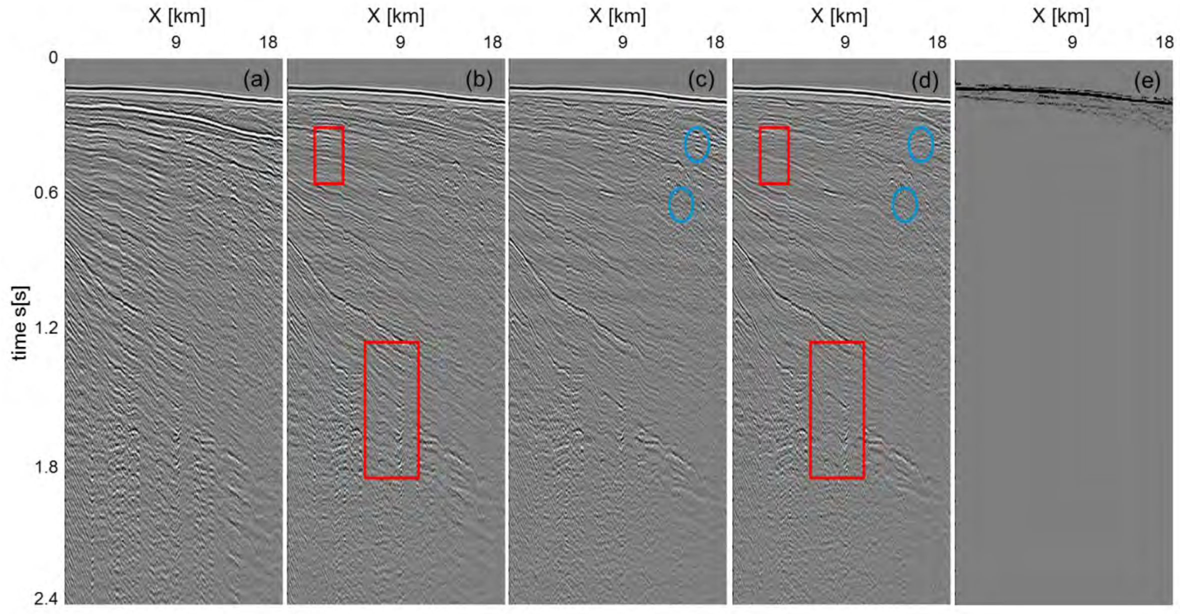

Figure 3 *Field data results after 10 iterations in common channel domain. (a) Input. (b) Surface-related multiple elimination (SRME). (c) Model-based water-layer demultiple (MWD).(d) EPSI. (e) Primary impulse response* X_0.

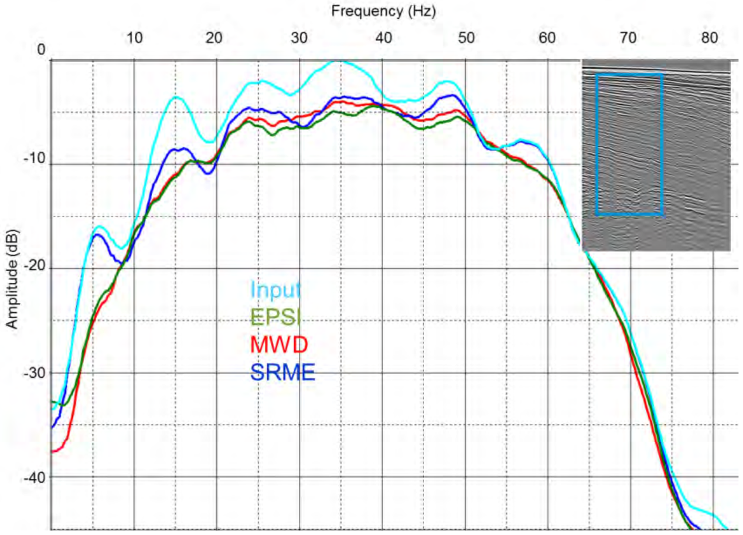

Figure 4 *Spectrum on stacks of input, EPSI, MWD, and SRME results for the field data example in the boxed area.*

The multiples were well reconstructed after 60 iterations, including most of the details from the water bottom features (Figure 2b). This multiple model was directly subtracted from the input, yielding the demultiple result (Figure 2c). The ringing multiple reverberations were mostly removed, with only a small residual from the short-period water bottom oscillation in the shallowest part of the data. The underlying primaries are now recognizable as an over-thrusted, faulted anticline.

Field Data Example

We again tested EPSI using the new picking strategy on a marine data set with a shallow water bottom of approximately 100 m offshore east Canada. On the fine-layer geological structures, multiples cut across primaries in many locations, and short-period reverberations of high-order multiples mask the primaries (Figure 3a). These reverberations make the multiple attenuation very challenging. As we stated earlier, EPSI has two main limitations on field data: (1) an extremely high computational cost and (2) wrong picks due to imperfect field data quality and data regularization. To mitigate those limitations, we targeted only shallow reflectors, which are the major multiple generators in shallow water. The picked water bottom looks complete and coherent after 10 iterations (Figure 3e). MWD is capable of modelling the water bottom and then predicting the water-layer multiples from it. Yet, in addition to the water bottom, EPSI picked additional strong reflectors (Figure 3e); besides the water-layer multiples, additional multiples generated by those reflectors were predicted. Figures 3b to 3d show subtraction results in the common channel domain with a 137.5 m offset. Because EPSI predicted more multiples from both the water bottom and shallow reflectors, we expected EPSI to remove more multiples than MWD in the circled areas (Figures 3c and 3d). Because SRME is affected by cross-talk issues, EPSI attenuated more high-frequency multiples in shallow areas and more low-frequency multiples in the deep areas as indicated by the red squares (Figures 3b and 3d). Furthermore, because the EPSI multiple model matched the input data better in both amplitude and phase, the subtraction was superior for EPSI. On the spectrum comparison, the results from EPSI and MWD better match the input data sets compared with SRME (Figure 4). However, EPSI removed more energy in the middle frequency range between 25-50 Hz when compared with MWD. Overall, EPSI attenuated more multiple energy than either MWD or SRME for this example.

Conclusions

We demonstrated that by using our method, EPSI can effectively attenuate surface-related multiples in shallow water. Using three-layer synthetic data sets, we proved that the input-picking strategy implemented in the first iteration can lead to correct and faster separation of primaries and multiples. It avoids running several iterations to correct wrongly picked events, which is a common challenge of EPSI. Our picking strategy can be extended to all primaries above the first multiple time.

The complex synthetic example and field data example showed that EPSI performed effectively in attenuating multiple energy. By only targeting shallow, strong multiple generators, the computational cost is greatly reduced, and the wrong picks can be mitigated. Additionally, accurate data regularization is critical for good results.

Acknowledgement

We thank CGG's multi-client data library for the field data example and CGG for permission to publish this research. We are grateful to Eric Verschuur and Gabriel Lopez from the Delphi consortium for helpful discussions. Special acknowledgements go to Chu-Ong Ting and Yan Huang for constructive suggestions and support of this research.

References

Baardman, R.H., Verschuur, D.J. van Borselen, R.G. Frijlink, M.O., and Hegge, R.F. [2010] Estimation of primaries by sparse inversion using dual sensor data: *80th SEG Annual International Meeting*, Expanded Abstracts, 3468-3472.
Berkhout, A.J. [1982] Seismic migration, imaging of acoustic energy by wave field extrapolation, A. Theoretical aspects: Elsevier (second edition).
van Groenestijn, G.J.A., and Verschuur, D.J. [2009] Estimation of primaries and near offsets by sparse inversion: Marine data applications. *Geophysics*, 74(6), R119-R128.
Lin, T. and Herrmann, F. [2013] Robust estimation of primaries by sparse inversion via one-norm minimization. *Geophysics*, 78(3), R133-R150.
Lopez, G., and Verschuur, D.J. [2012] SRME and estimation of primaries by sparse inversion: A hybrid approach. *82nd SEG Annual International Meeting*, Expanded Abstracts, 1–5.
Verschuur, D.J. [2013] Estimation of primaries by sparse inversion including the ghost: *83rd SEG Annual International Meeting*, Expanded Abstracts, 4094-4100.
Verschuur, D.J., and Berkhout, A.J. [1997] Estimation of multiple scattering by iterative inversion, part II: practical aspects and examples: *Geophysics*, 62(5), 1596-1611.
Wang, P., Jin, H., Xu, S., and Zhang, Y. [2011] Model-based water-layer demultiple: *81st SEG Annual International Meeting*, Expanded Abstracts, 3551–3555.